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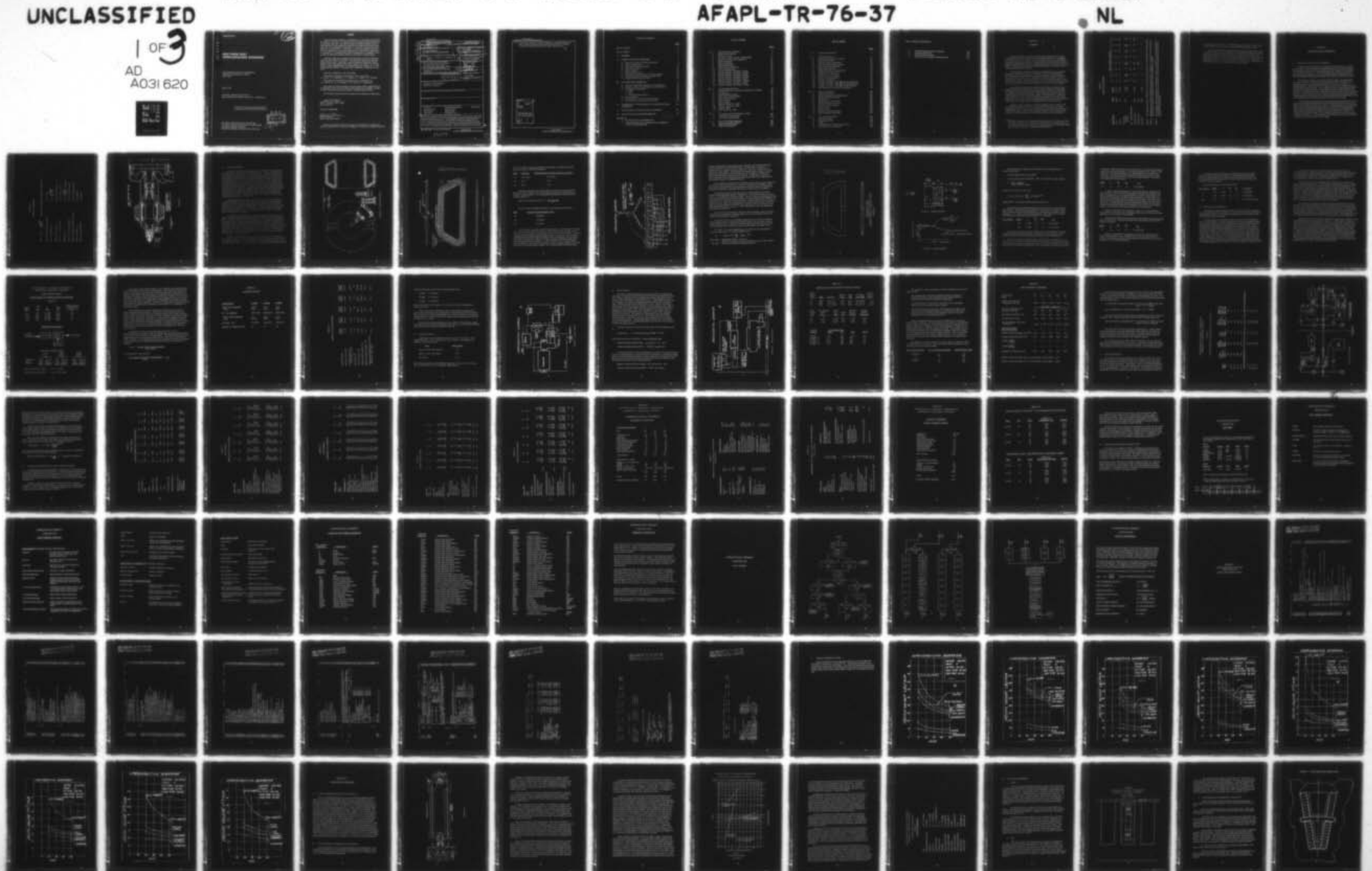

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HIGH POWER STUDY SUPERCONDUCTING GENERATORS

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION
LIMA, OHIO

MARCH 1976

TECHNICAL REPORT AFAPL-TR-76-37
FINAL REPORT FOR PERIOD 2 JUNE 1975 - 1 MARCH 1976

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This final report was submitted by Westinghouse Electric Corporation, under Contract F33615-75-C-2068. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3145, Task 32 and Work Unit 32 with Hugh L. Southall/AFAPL/POD-1 as Project Engineer In-Charge. A. E. King of Westinghouse Electric Corporation was technically responsible for the work.

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This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the results of a design study of light weight, high power electrical generators in the 10 to 50 Megawatt range with output voltages up to 200 kV dc (after rectification). Superconducting machines representing the latest technology were the focus of the study; non-superconducting machines utilizing the most advanced conventional design technologies were also studied to develop comparable performance data. Turbine requirements and integration

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20. features were studied to assure compatibility. A separate analysis of MHD electrical generator designs was also carried out to highlight comparable performance data for that type of power source.

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SECTION I

SUMMARY

The object of the study was to determine the weights and volumes of light weight electrical generators for airborne applications. Machines in the range of 10 to 50 MVA, 20 to 200 KVDC* and with special duty cyles were studied (see Table I-1). Sixty percent of the effort was directed toward superconducting machines; thirty percent of the effort was directed toward conventional (non-superconducting) machines; ten percent was directed toward MHD and turbines.

A concentrated effort was directed toward determining the minimum weight and volume as a function of voltage. Due to the necessity of thicker and more sophisticated insulation for the high voltages studied, the weight and volume of the conventional generating systems increase rapidly with voltage. The specified range of 20 to 200 KVDC could be satisfied with the superconducting machines, but the highest practical voltage for the conventional machine was determined to be less than 100 KVDC.

The high power generators studied were required to supply output power at specific short intervals or duty cycles. However, it was determined that the superconducting machines should be (and were) designed to operate at full load continuously. Little could be gained in terms of saving weight and volume had the machines been designed for a specific short-term duty cycle. For the conventional machines, the reverse was found to be true. As a result, they were designed to operate into a limited duty cycle: full power output for approximately two minutes or less.

Machines were designed to meet the specific power, voltage, and duty cycles specified in Table I-1. The sizes of the machines varied significantly with the power and voltage level, but the basic configuration remained the same. Duty cycles had minor impact on the overall system, and had no significant affect on the critical internal design parameters

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* All output voltages in the report are given in terms of dc volts, assuming all of the ac output of the machine is rectified in a full wave bridge. The relationship between the ac and dc voltages as well as the resulting power factor on the machines is summarized in Appendix A.

TABLE I-1

SUBSYSTEM PARAMETERS

PARAMETERS	UNITS	RANGE	POINT DESIGN NUMBER 1	2	3	4	5	6	7	8
Power	MWE	10-50	10	10	25	25	25	25	50	50
Voltage	KV	20-250	60	60	60	60	60	60	200	200
Duty Cycle										
On Time	SEC	1-120	21	21	4	120	21	21	25	12
Off Time		2-300	30	300	4	N/A	30	300	N/A	78
No. of Cycles/Mission			3	3	16	1	3	3	3	10
Total Run Time	SEC	30-120	63	63	64	120	63	63	75	120
Start-up Time	SEC		1	1	1	N/A	1	1	1	1
Idle Time	MIN	5-120	0	0	0	0	0	0	0	0

NOTE 1: The subsystem shall be designed for a 100 mission life (total life = 100 X number of cycles above).

NOTE 2: Electrical sources shall be designed to produce 60 KV, if possible. If the source cannot achieve 60 KV directly, design for minimum weight and volume regardless of voltage.

NOTE 3: The subsystem shall be designed for 1 second start-up time, if possible. If one second start-up is not possible, design for minimum start-up time. If start-up time is greater than 3 seconds, provide for 10 minutes idle.

selected for the machines. The expendables and sizing of the external cooling system are, of course, very dependent upon duty cycle.

A computer code was written, utilizing the design data of the study, to provide the Air Force an algorithm for calculating weights and volumes of machines with intermediate output power and voltage levels. Any machine parameters in the range given in Table I-1 can be input, the output being the weight, volume, and external requirements of the power generating system. The code was written in Fortran to be compatible with CDC 6600 computer at Wright Patterson Air Force Base.

SECTION II

SUPERCONDUCTING GENERATORS

A. Selection of Internal Design Parameters

Certain internal parameters were selected and treated as a constant for this study. They included the peripheral velocity of the field winding, the maximum field in the superconducting winding and the current density in the armature conductors. These parameters were defined numerically and were based upon proven technology obtained from the USAF Superconducting Generator Development Program under Contract F33615-71-C-1591.

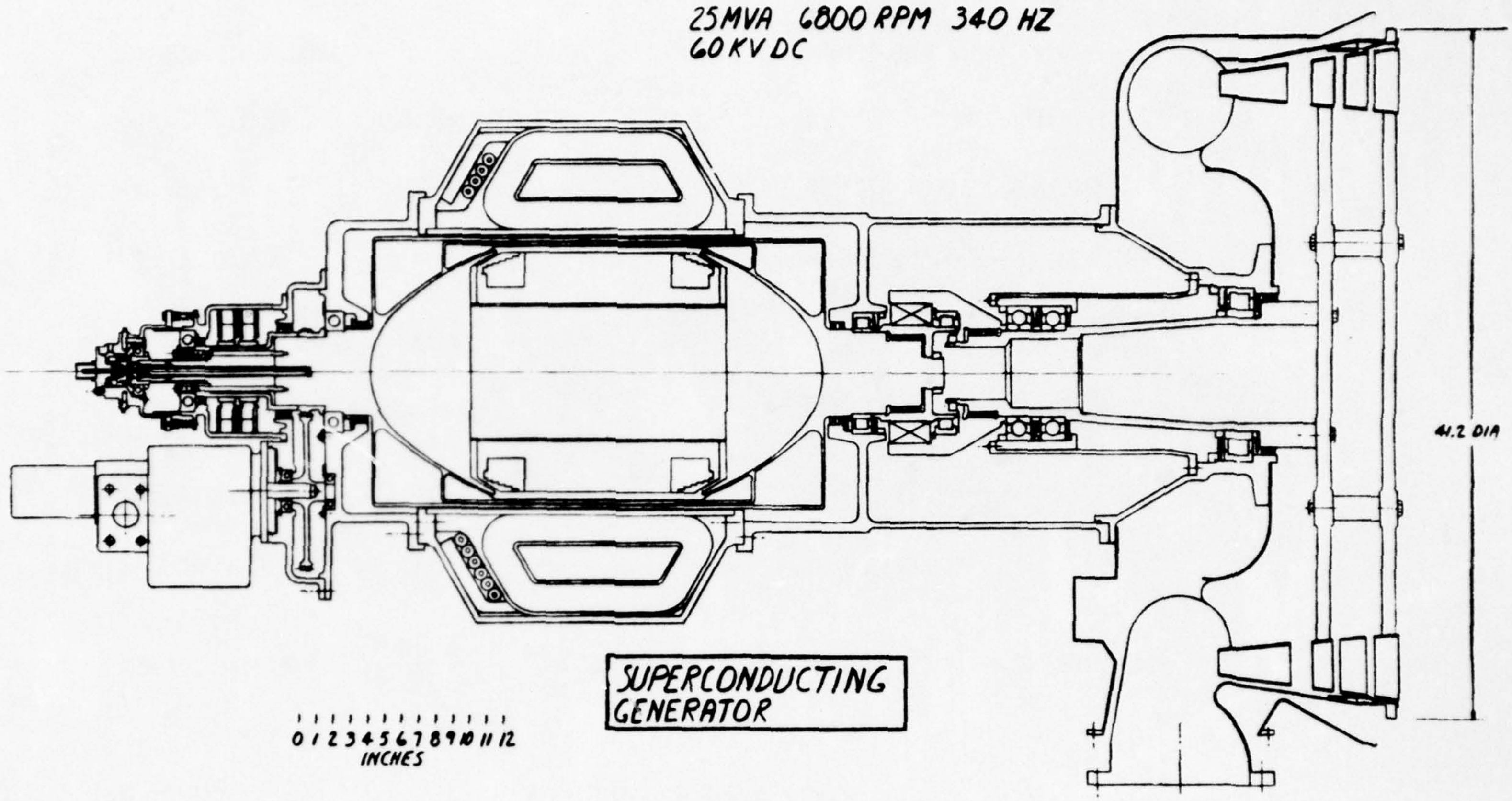
The number of poles in the generator was treated as an independent variable, and both 4-pole and 6-pole machines were analyzed. The rotational speed is an important parameter in the design of rotors for superconduction. Since there was no intent to use a speed changer between the generator and the turbine, it was imperative that a speed and power relationship be established early in the program to insure compatibility of subsystems. A speed versus power relationship was selected at the first working session of all contractors and was used to develop the weight and volume of a superconducting generator for all of the specified external parameters. Table II-1 summarizes the key internal parameters used for this study.

A conceptual configuration for the superconducting generator was developed from the specified requirements and from the development efforts being funded under Contract F33615-71-C-1591. Probable advances in the development of superconducting generators were not considered when experimental verification of those potential improvements could not be phased into the overall program schedule as defined in the Work Statement. Those to be verified in time were included. The concept which evolved from this study is shown in Figure II-1. The approach to and evaluation of this configuration is presented in other sections of this report.

TABLE II-1

DESIGN PARAMETERS

RPM = 5656 $\sqrt{\frac{50}{MVA}}$	BASED ON TURBINE-GENERATOR INTERFACE
ROTOR PERIPHERAL VELOCITY =	420 FT/SEC
FIELD WINDING OD =	17.0 $\sqrt{\frac{MVA}{50}}$
STATOR WINDING ID =	FIELD WINDING OD + 2.6
NUMBER OF ROTOR POLES	4 POLES OR 6 POLES
FREQUENCY =	47.13 $\sqrt{\frac{50}{MVA}}$ (POLES)
STATOR CURRENT DENSITY =	16,000 AMPS/$(\text{INCH})^2$
FIELD WINDING CURRENT DENSITY =	153,228 AMPS/$(\text{INCH})^2$
FIELD CURRENT =	280 AMPERES
MAX. FIELD INTENSITY =	4.6 TESLA



25MVA 6800 RPM 340 HZ
60 KV DC
41.2 DIA
SUPERCONDUCTING GENERATOR
0 1 2 3 4 5 6 7 8 9 10 11 12
INCHES

FIGURE II-1

B. Stator Configuration

Two types of armature windings were investigated to find the most efficient way to produce the desired voltage. First the standard lap winding for aircraft generators was investigated. In this winding, the coils sides are approximately one pole pitch apart so that at any instant the sides of each coil are under adjacent poles. A winding with coils of this shape must lie in two layers with the side of one coil resting above or below the side of a different coil. The advantage of this coil is that both sides generate voltage. However, the side of one coil resting above or below the side of another coil causes a large voltage gradient between the layers and insulation is required at this location. Moreover, the hair pin cross-over to the adjacent pole in the ends of the coil causes the conductors of one phase voltage to lie above or below conductors of a different phase voltage. Large space and extra insulation are required to make these hairpin crossovers.

Lap windings were evolved over the power range of interest for a voltage of 60 KVDC. In all cases, the length of the end turns exceeded the active length of the coils by a factor greater than two (2). For example, coils for a 25 MVA, 60 KVDC had a conductor length of 35.4 incnes with an active length of only 15.6 inches. It was concluded that these long end turn cross-overs were not practical and a Gramme ring winding was a more practical approach.

In a Gramme ring winding, the coils are placed around the iron ring which provides the flux path between adjacent poles as shown in Figure II-2 . The side between the iron ring and the rotor lies in the time varying flux field. Hence, this side of the coil generates voltage. The other side of the coil (outer conductors) does not generate voltage but produces an electrical connection for the side of the coil that is in the field. Obviously, this winding becomes inefficient when the active length of the generator is greater than the length required for the coil to re-enter at the other end of the iron ring. This is not the situation for the superconducting generators investigated for this application.

A Gramme ring winding provides several advantages for generation of the desired voltages. First, the winding can be formed from coils whose individual conductors are series connected in the radial directions as shown in Figure II-3 . Thus, the voltage potential between adjacent radial conduc-

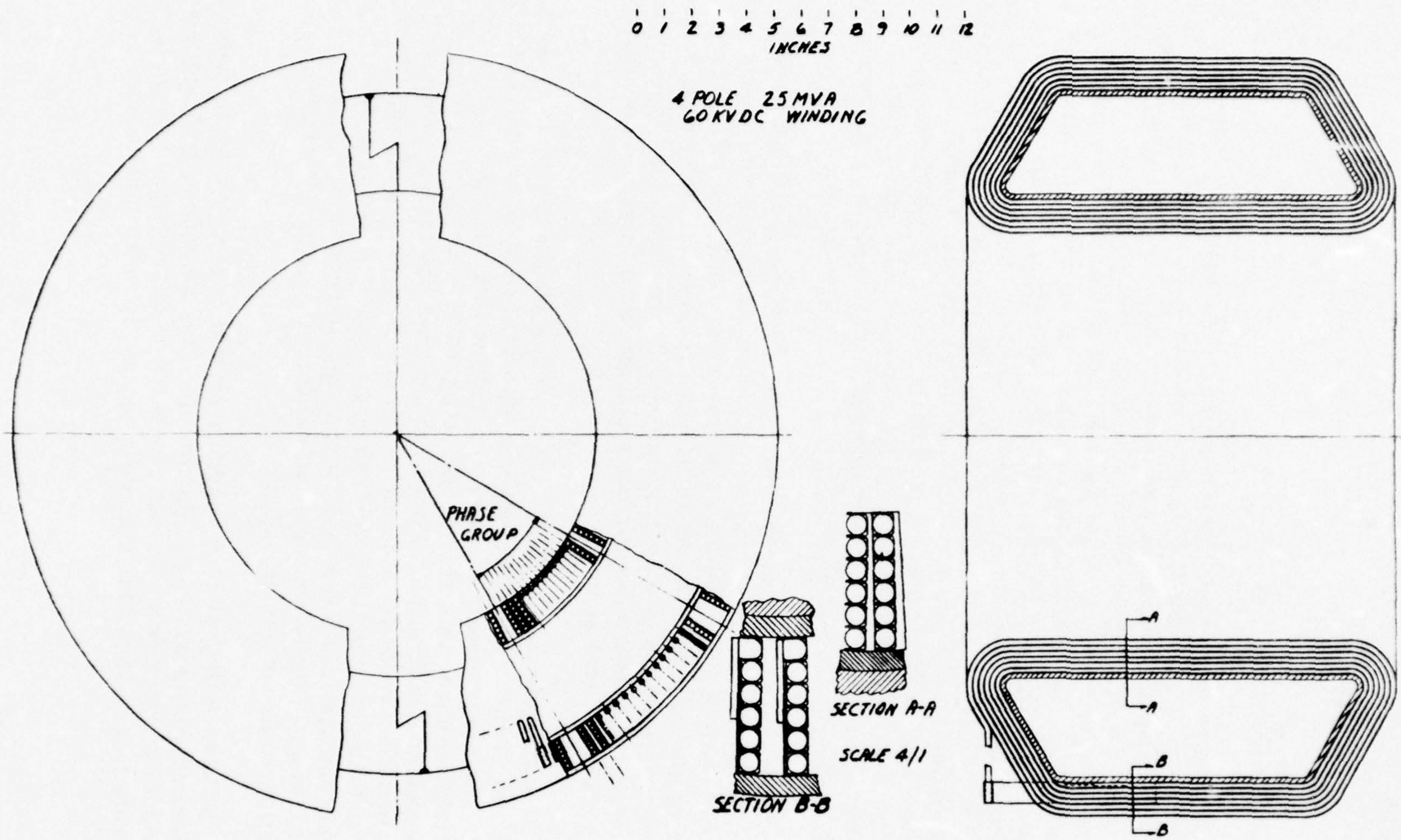


FIGURE II-2 Gramme Ring Winding

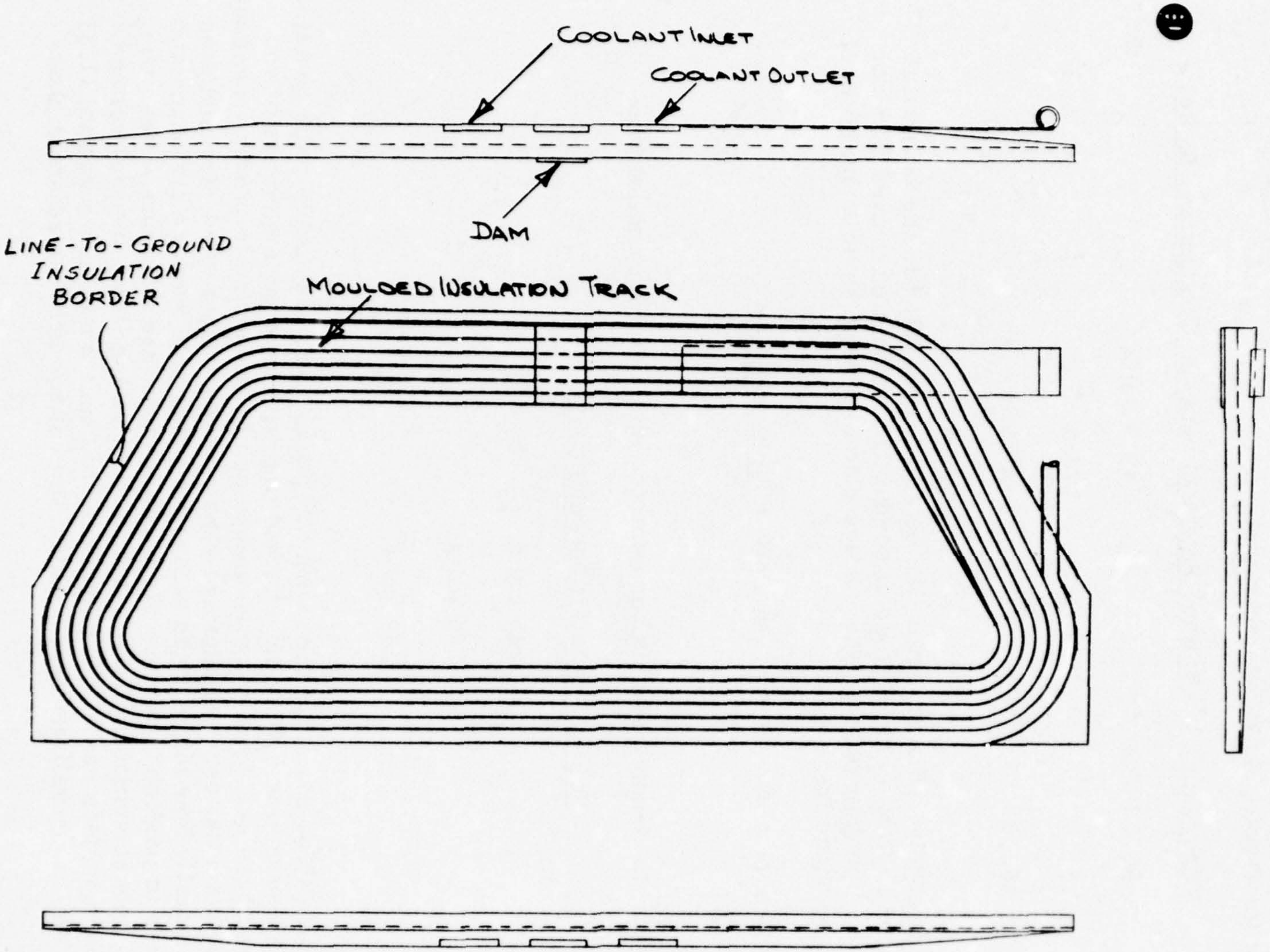


FIGURE II-3 MOLDING FOR COIL

tors is one-half of the turn voltage for the machine. Examples are given below for 4-pole, 60 KVDC generators:

MVA	Volts/Turn	Voltage Potential between Conductors, Radial
10	98.5 Volts	49.3 Volts
25	153.3	76.7
50	143.8	71.9

Secondly, adjacent coils can be series connected in the tangential direction to form a single group of conductors which are removed from conductors of another phase. The voltage potential between adjacent coils of the same phase is:

$$\text{Number of Conductors per Coil} * \frac{\text{Volts per Turn}}{2}$$

For the 4-pole, 60 KVDC generators, this voltage potential was:

MVA	Voltage Potential Between Coils
10	246 Volts
25	230 Volts
50	216 Volts

In a three phase machine with 60° phase belts, each pole pitch contains three phase groups. Since the Gramme ring winding contains groups of conductors of the same phase, these groups can be connected to produce a minimum voltage potential between adjacent phase groups. Figure II-4 demonstrates schematically how these phase groups for a four pole machine are connected in series to produce line voltage. It can be noted the maximum voltage potential between adjacent groups is 1.1456 times the line to neutral voltage. Six pole machines can also be connected to cause a minimum potential (1.1586 times line to neutral) between groups. The voltage between adjacent phase

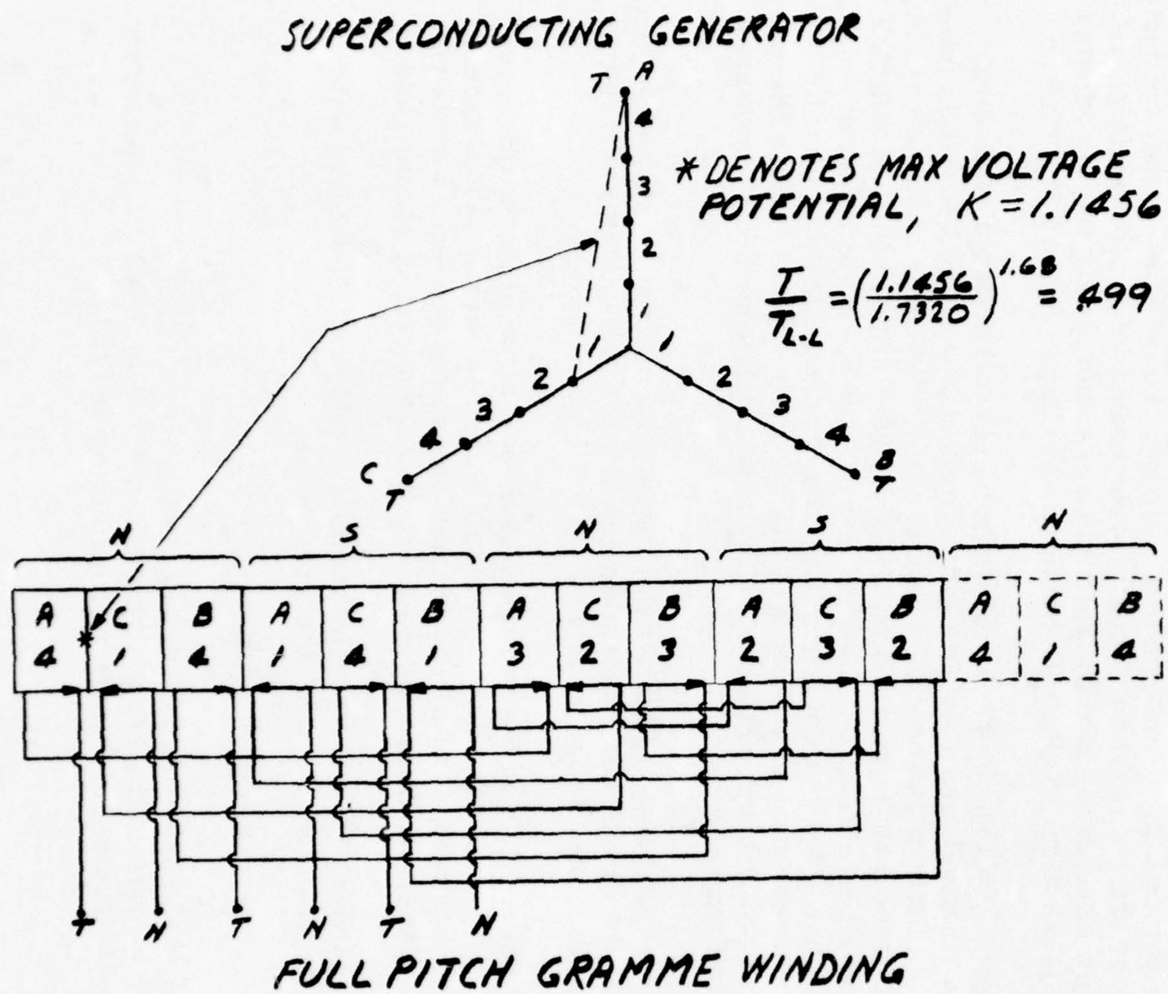


FIGURE II-4 Schematic of Phase Group Connections for Gramme Ring Winding

groups represent the largest potential in a Gramme ring winding (32 KV and 107 KV for 60 KVDC and 200 KVDC output, respectively). Therefore, a special barrier is required at these locations. Figure II-5 shows the configuration of this barrier. Fortunately, this barrier does not have a complex shape and compression molding techniques are available to produce this barrier with essentially zero microvoid content. Furthermore, dielectric tests including corona discharge and power factor tests can be performed on each barrier before it is committed for use.

The outstanding advantage of the Gramme ring winding is that conductors of one phase are not required to cross-over conductors in a different phase. This feature eliminated the critical problem associated with the lap winding and made it practical to generate the desired voltages (up to 200 KVDC).

A review was made of test results from several decades of studies, within the Westinghouse Electric Corporation, of insulating barriers in transformer oil in uniform and divergent fields. From this data, an empirical formula was established which gives the breakdown strength (volts/mil) of WEMCO "C" transformer oil as a function of the oil gap in a quasi-uniform field at approximately 720 torr. With this relationship, the required thickness of solid insulation was established so the actual volts per mil in the oil is equal or less than breakdown strength of the oil. This relationship used the parameters described in Figure II-6.

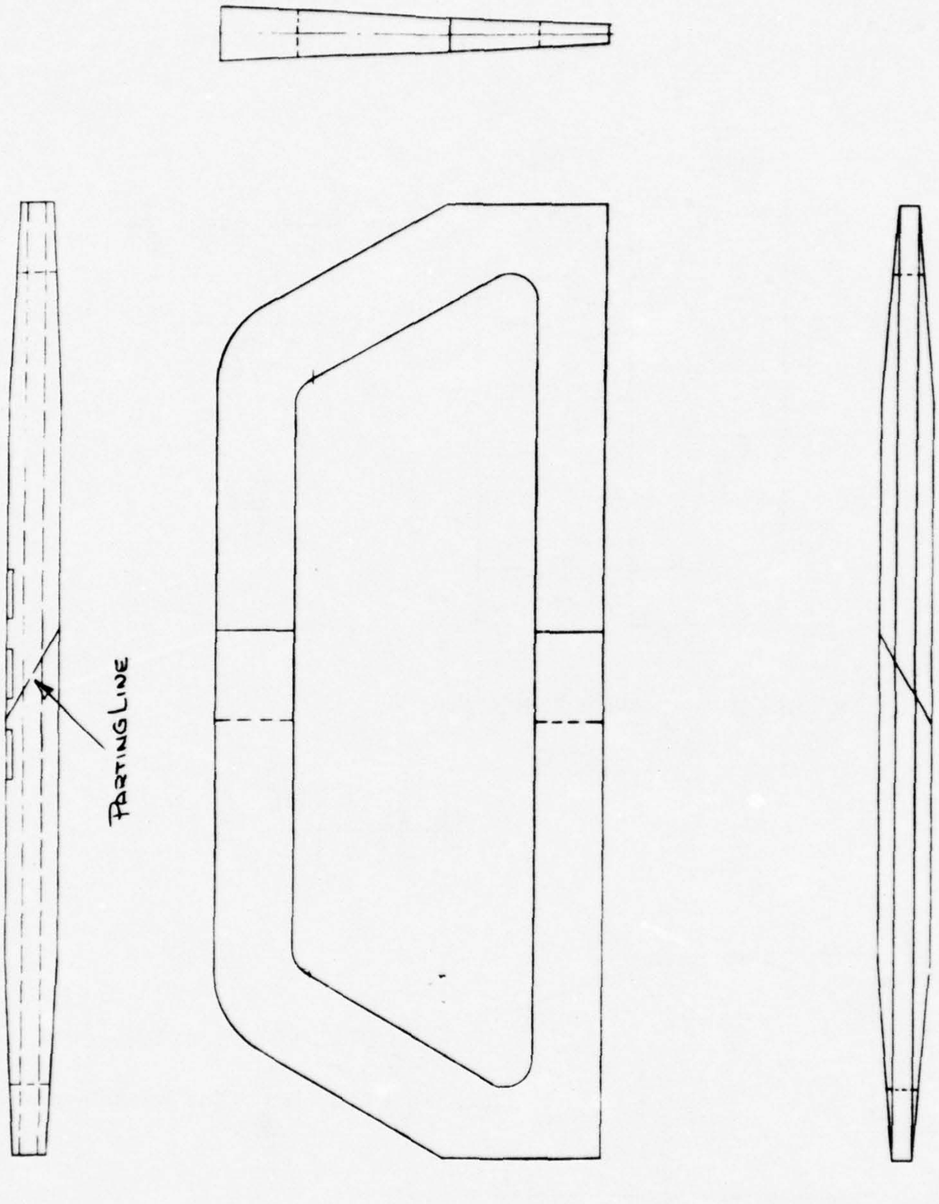
It was found that the barrier thickness has a maximum value when plotted against the oil gap for constant values of the total potential across the spaces as illustrated in Figure II-7.

The value of T'_2 is the important parameter since a barrier thickness greater than T'_2 will not cause the electric stress in any oil gap to exceed the breakdown stress. Oil will be present around the conductors since the cooling passages are formed by virtue of round conductor in square slots.

The value of T'_2 was established as a function of the total applied voltage. Empirically, T'_2 can be expressed as:

$$T'_2 = 1.246 \times 10^{-4} \frac{\epsilon_i}{\epsilon_o} (KV_B)^{1.68}$$

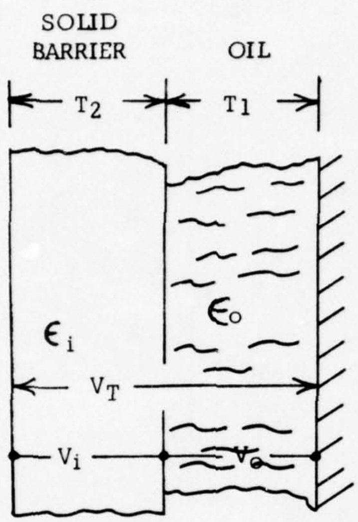
Where KV_B = Breakdown Voltage, kilovolts.
T = Barrier Thickness to prevent breakdown in all oil gap, inches.
ϵ_i, ϵ_o = Dielectric Constant of Insulation and Oil



BARRIER FOR
PHASE GROUP SEPARATION

FIGURE II-5

$$\frac{V_o}{V_i} = \frac{T_1 \epsilon_i}{T_2 \epsilon_o}$$



$$V_T = \frac{4\pi Q}{A}\left(\frac{T_1}{\epsilon_o} + \frac{T_2}{\epsilon_i}\right)$$

$$\frac{V_i}{V_T} = \frac{1}{1 + \frac{T_1 \epsilon_i}{T_2 \epsilon_o}}$$

$$\frac{V_o}{V_T} = \frac{1}{1 + \frac{T_2 \epsilon_o}{T_1 \epsilon_i}}$$

FIGURE II-6 BARRIER SCHEMATIC

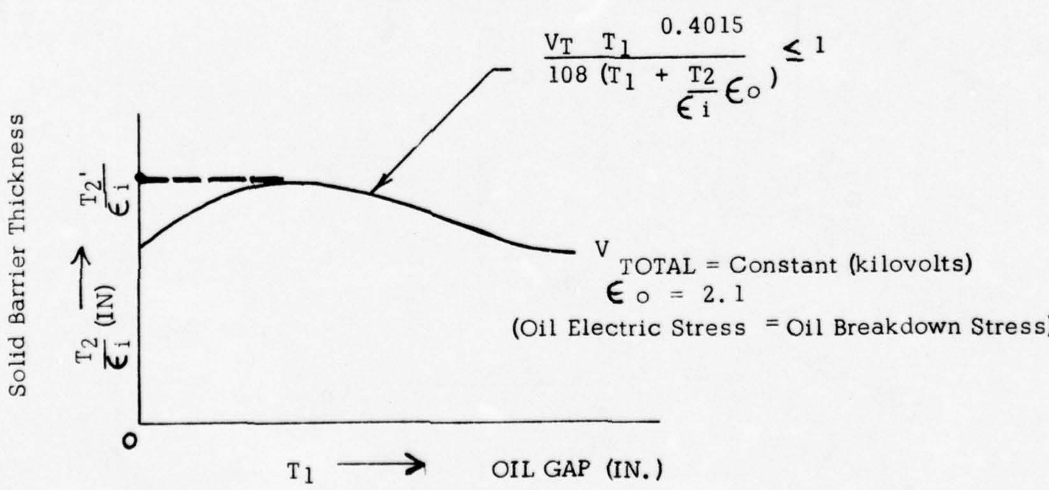


FIGURE II-7 BARRIER THICKNESS

This equation was changed to be reflective of the design value of voltage based upon:

- Design Voltage must be $\leq \frac{1}{2}$ KVB
- Design Voltage (line to ground) = 46% of the rectified output voltage
- $k = \dfrac{\text{Local voltage}}{\text{Line to neutral voltage}}$

An equivalent expression becomes:

$$T'_2 \geq 1.083 \times 10^{-4} \frac{\epsilon_i}{\epsilon_o} (k * KVDC)^{1.68}$$

Where KVDC = DC Voltage with full wave rectification.

The phase group separator represents a critical barrier for the Gramme ring winding. This will be a high pressure molding and one choice of material is a glass fiber reinforced polysulfone. The dielectric constant for this material is 3.5. Hence, the required thickness of the barrier for a voltage of 60 KVDC in oil with dielectric constant of 2.1 becomes:

No. of Poles	KVDC	k	ϵ_i	ϵ_o	T'_2
4	60	1.1456	3.5	2.1	0.220 inches
6	60	1.1586	3.5	2.1	0.224 inches

The required thickness for this barrier from the standpoint of insulation is about one-quarter inch. However, a thickness of 0.4 inch was used for the point design at 60 KVDC for mechanical (structural) considerations.

A large tangential and radial voltage potential does not exist across the moldings for the conductor tracks as previously discussed. Nevertheless, this part as well as the phase group separator serve as a barrier between the exterior envelope of the conductors and ground. Thus, essentially zero microvoid content

is required. When these barriers are produced in a high pressure mold,this requirement can be maintained. The logical material for the molding with tracks for the conductor would be the same material as the phase group separators. Figure II-3 illustrates the border distance around the outer conductors which would serve as the line-to-ground barrier. The dimension required for this border is:

KVDC	k	ϵ_i	ϵ_o	T'_2
60	1.0	3.5	2.1	0.175 Inches

It can be noted from Figure II-3, the border does not encompass the entire molding. The remainder of the border is provided by the bore seal. After the cylindrical seal is inserted through the bore of the winding, the winding and bore seal are wrapped with a composite of epoxy resin and glass. It is noteworthy that this composite only needs to perform a structural function since the electric field will be attenuated in the molding for the coils. A semiconducting material between the molding and the outer wrapping insures that a breakdown voltage will not occur in the wrapping. Hence, this composite does not need to be free of microvoids.

The bore seal serves two functions. First, it is a structural part and secondly, it serves as an insulating barrier from line to ground voltage. Therefore, it must be free of microvoids.

A glass fiber reinforced composite offers reasonable mechanical properties for a bore seal. The required thickness of this barrier for a 60 KVDC generator becomes:

KVDC	k	ϵ_i	ϵ_o	T'_2
60	1.0	4.1	2.1	0.184 inches

However, mechanical considerations for the bore seal show that a greater thickness than this is required for the 10 to 25 MVA machines. Hence, the dielectric constant of the composite structure was not a critical parameter for the 60 KVDC generator.

The required barrier thickness at 200 KVDC was based on materials with a dielectric constant of 2.5 and 2.1. The material with the higher dielectric constant was used for the moldings (high density Polyethylene) and the material with the low dielectric constant (Flurocarbon) was used for line to ground insulation.

The barrier thickness at 200 KVDC becomes:

No. of Poles	KVDC	k	ϵ_i	ϵ_o	T'_2, Inches
4	200	1.1456	2.5	2.1	1.19 Moldings
6	200	1.1586	2.5	2.1	1.21 Moldings
N/A	200	1.0	2.1	2.1	0.80, Line-to-Ground

C. Fast Start-Up Considerations

The Statement of Work requires a one second start-up time, if possible. If a one second start-up is not possible, then the system shall be designed for minimum start-up time. If the start-up is greater than three seconds, an idle for ten minutes shall be provided.

A normal start-up of a generator implies that the rotor is accelerated from zero to full speed. For the point designs for the superconducting generators, a steady torque of only 14% of the machine torque at rated power would accelerate the rotor from zero to full speed in one second or less. Hence, the transmission of torque for acceleration from the turbine into the generator rotor does not appear to be any problem since the shaft will be designed for fault torques which are greater than the torque at full load. The problem with a rapid rotor acceleration is associated with the heating that occurs in the field winding. First, the helium in the rotor undergoes compression by virtue of the centrifugal acceleration. This compression causes a temperature rise of about $1^{\circ}K$ (when a static rotor is accelerated to design speed). Secondly, the changing centrifugal loads cause the container to expand and permit motion of the superconducting wire. This motion can cause heating by virtue of friction.

A start-up of a machine normally implies that full excitation is achieved during the start-up period. This implies that the superconducting field winding must undergo full excitation in approximately one second for this application. This is not the most favorable way to energize the superconducting field for the reasons discussed here.

The rapid change of field current causes heating in the normal conductive materials in the rotor. This heating is not limited to just the copper in the superconducting wire, but also occurs in the heat exchanger in the field, the container around the winding and the electro-thermal shield. This heating could place unusual demands upon the cooling system. In addition, a large dc power source is required to charge the field even though very little power (~ 300 watts) is required to maintain the field. A one second ramp of the field current at a constant voltage for the point designs is given in Table II-2 with a cursory evaluation of the weight of an aircraft generator with a transformer-rectifier unit for serving this power.

It should be noted that the amount of field power required for charging the field under these conditions is about the same as the power required for excitation of conventional generators of equivalent ratings. If the charging time is increased from one second to one minute, the amount of power would be decreased by a factor of ~60 whereas a conventional resistive field winding would require about the same amount of power. The estimated weight of a power source for a charging time of one minute is given in Table II-2.

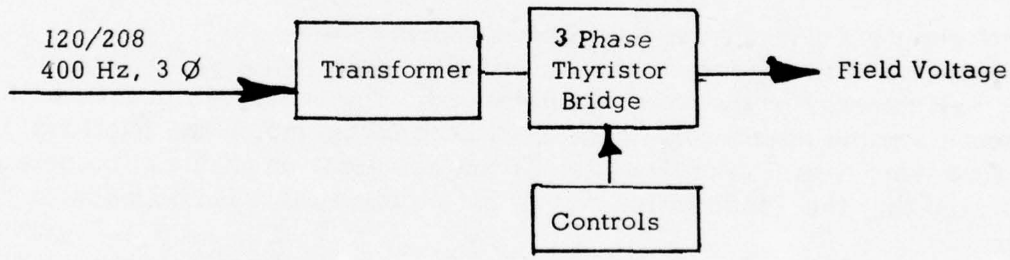
Experimental work is presently underway to determine the impact of rotor acceleration upon the superconducting state of a field winding. However, until this information is available, it shall be assumed that a rapid acceleration of the rotor to design speed with concurrent charging of the field over a period of one to three seconds would produce a thermodynamic state which would not allow present day conductors to remain superconducting. Thus, in order for a superconducting generator to provide immediate electric power on demand, the rotor should be idling near design speed with full excitation. This mode of operation can be accomplished by using an overriding clutch between the turbine and generator. The acceleration of the rotor up to the idling speed can be accomplished by using a hydraulic motor, fluid from the aircraft hydraulic system, and an auxiliary gear box.

POWER REQUIRED TO CHARGE THE FIELD IN ONE SECOND

TABLE II-2

Rating, MVA	$L\frac{di}{dt}$ Volts	I_f Amp	Power KW	Estimated Weight Of Power Source Lbs.
10	362	0 to 280	101.3	75
25-4	893	0 to 280	249.9	160
25-6	1076	0 to 280	301.4	-
50-4	2322	0 to 280	650.2	310
50-6	2674	0 to 280	748.8	-

GENERATOR FIELD CONTROL



ONE MINUTE CHARGING TIME

	10 MVA 7 Volt		25 MVA 4-Pole 16 Volt		50 MVA 4-Pole 40 Volt	
Transformer	6 Lb.	60 in.^{3}	12 Lb.	120 in.^{3}	20 Lb.	200 in.^{3}
Bridge	25 Lb.	1100 in.^{3}	25 Lb.	1100 in.^{3}	25 Lb.	1100 in.^{3}
Controls	2 Lb.	150 in.^{3}	2 Lb.	150 in.^{3}	2 Lb.	150 in.^{3}
	33 Lb.	1310 in.^{3}	39 Lb.	1370 in.^{3}	47 Lb.	1450 in.^{3}

Weight of Power Supply (Lbs) = 27. + .52 * MVA

Volume of Power Supply (FT^3) = .723 + .00278 * MVA

The auxiliary gear box is mounted on the antidrive end of the generator on the outboard side of the main rotor bearing. Two power take-offs are required, one at the speed of the rotor and one at the speed of the lubrication pump (~ 4000 RPM). The input power is supplied by the hydraulic motor at 4000 RPM. A speed increase from the motor to rotor is made in a single step. Gear sizes and data for a system which provides adequate offset of the input and output shaft are given in Table II-3. Undoubtedly, the weight for each rating would be slightly different. However, a detail design is required before these small variations can be defined, and they were of no consequence to the present study.

The hydraulic motor must be adequate to cause the rotor to idle at design speed with full excitation. The losses in the machine during this mode of operation are (1) friction and windage losses in the clutch, bearing, seals, gears, and brushes; (2) iron losses in the shield; and (3) eddy current losses in the conductors. In addition , power must be supplied to the lube pump. Power requirements and other parameters for the hydraulic motor are summarized in Table II-4 for several designs. A specific power of 4.5 horsepower per pound was used to obtain the weight of the motor; the fluid flow rate is based upon a motor efficiency of 80% at 4000 RPM with a 3000 psi inlet pressure.

Acceleration of the rotor would be performed first, that is, with the generator unexcited so that the primary work required from the motor is the kinetic energy of the rotor at idle speed. The acceleration time will be dependent upon the speed-torque characterisitc of the motor and frictional drag. However, a first approximation of the acceleration time can be obtained by assuming that the acceleration torque acting upon the rotating mass is equal to:

$$\text{Torque} = \frac{\text{Losses Excited} - \text{Loss Unexcited}}{\text{Rated Speed}}$$

The acceleration time becomes:

$$\frac{\text{Rotor Moment of Inertia} * \text{Design Speed}}{\text{Torque}} = \text{Time}$$

TABLE II-3

AUXILIARY GEAR BOX

DESIGNATION	10 MVA	25 MVA	50 MVA
INPUT GEAR DIAMETER	11.07	9.72	8.53
RPM	4000	4000	4000
NO. OF BEARINGS	(205) (205)	(206) (205)	(206) (205)
OUTPUT GEAR DIAMETER	3.5	4.85	6.04
RPM	12,647	8000	5656
BOX DIM. (IN.)	16 X 12 X 3	16 X 11 X 3	16 X 10 X 3
WEIGHT OF GEAR BOX, LBS.	20	20	20

TABLE II-4

HYDRAULIC MOTOR PARAMETERS

Generator Rating	10 MVA 4-Pole	25 MVA 4-Pole	25 MVA 6-Pole	50 MVA 4-Pole	50 MVA 6-Pole
Losses in Clutch, HP	9.00	22.50	22.50	45.00	45.00
No Load Losses with 100% Excitation, HP	40.79	71.92	111.85	83.20	118.01
Lube Pump, HP	.25	.25	.25	.25	.25
Gear Box Output, HP	50.04	94.67	134.6	128.45	163.26
Hydraulic Motor Output, HP	52.13	98.61	140.21	133.80	170.06
Weight of Hydraulic Motor, Lbs	11.6	21.9	31.2	29.7	37.8
Hydraulic Fluid Required @ 3,000 psi Motor Eff. = 80% (gpm)	37.2	70.4	100.1	97.1	121.5

Typical acceleration times for the 4-pole machines are:

10 MVA: 2.5 Minutes

25 MVA: 2.1 Minutes

50 MVA: 1.6 Minutes

These acceleration times appear to be congruous with the allowable ten minutes for idle.

Once the rotor has reached the idling speed and the thermodynamic state of the field winding has stabilized, the field winding can be energized. The charging time could be approximately one minute in place of one second which reduces the weight of the power supply and the demands upon the field winding cooling system.

It should be noted the reduction of the weight of the dc power supply (see Table II-3) with the slower charging time more than offsets weight penalty associated with the hydraulic motor and gear box.

D. Lubrication System

A schematic of the lubrication system is given in Figure II-8. The combined weight of the components in this system is 34 pounds and includes the following items.

Item	Weight (Lbs)
Pump and Scavenge Elements	5.2
Valves, Lines, and Filters	16.8
Oil Cooler	12.0

The lube pump operates at 4000 RPM and provides 3.6 gpm of oil at 30 psig with an input power of 0.25 horsepower (approximate).

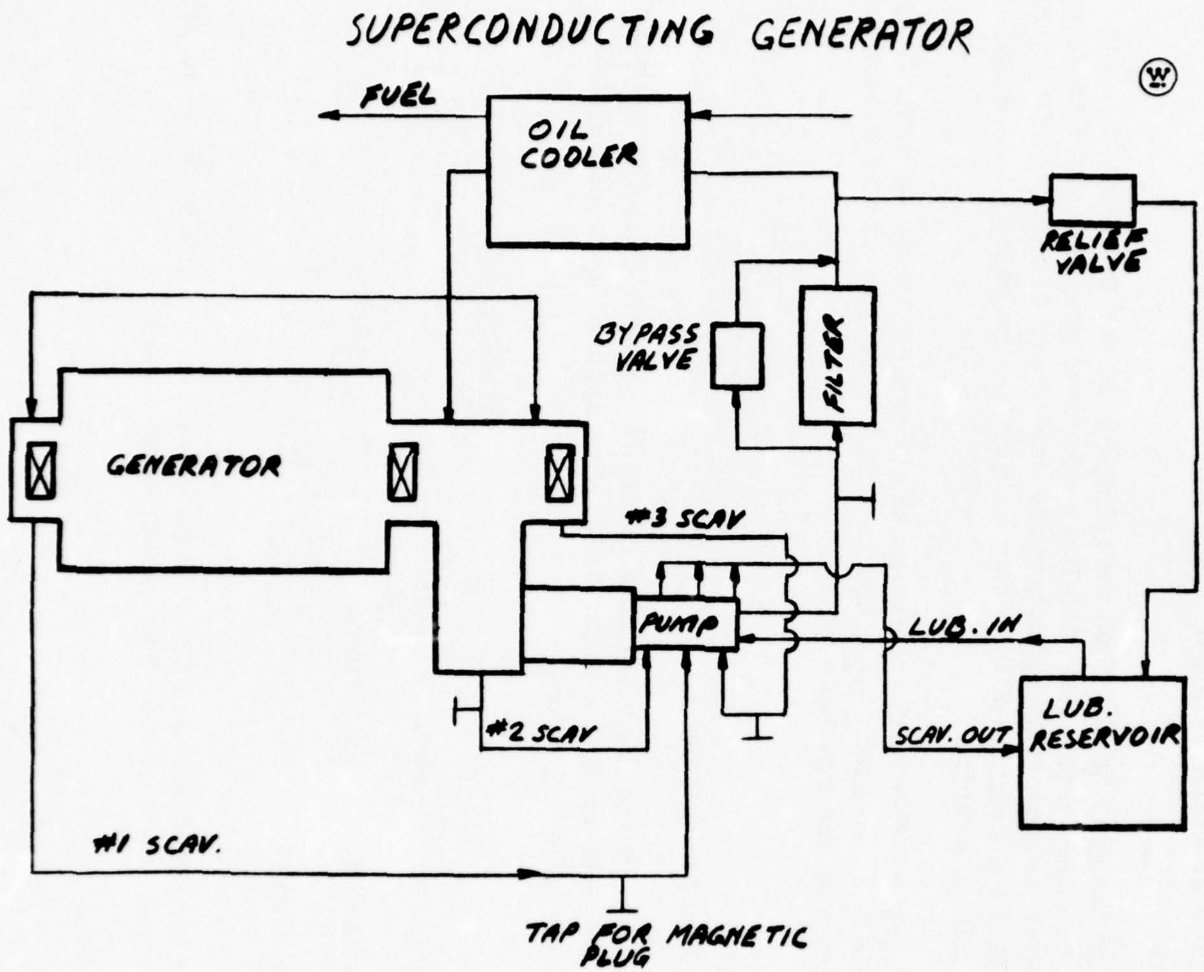


FIGURE II-8 Lubrication System

E. Stator Cooling

An electric motor/pump/reservoir unit is required to circulate the tranformer oil through the external heat exchanger as illustrated in Figure II-9. These components are integrated into a sealed package with the electric motor submerged in the transformer oil. This eliminates the need for a rotating seal and any contamination from harmful gases via such a seal. Electric power from the aircraft (220 volts, 3 phase, 400 Hz) is used by the motor and a Gerotor element is used to pump the oil. Part of the assembly is an expandable tank which accommodates the thermal expansion and contraction of the oil in the system. An external force is maintained on the expandable tank to keep the system under a positive pressure at all times. This feature is necessary so that any leakage always causes an outward flow of oil. The weight and volume of the motor/pump/tank unit depend upon the flow requirements for the stator/heat-exchanger system. Typical parameters for three wet motor designs are given in Table II-5. An estimated weight and volume for several point designs are presented also.

The flow required for cooling the stator with a 35°F temperature rise is:

$$\text{Gal per Min} = \text{Full Load Stator Losses (KW)} * 0.4658$$

Using the data given in Table II-5, it was established that:

$$\text{Weight Tank/Motor/Pump (lbs)} = \text{gal per min} * .13 \text{, and}$$

$$\text{Volume Tank/Motor/Pump } (FT^3) = .001736 * \text{gal per min.}$$

A significant portion of the total weight and volume of the stator cooling system is contributed by the lines and fittings necessary to connect the stator, pump, and heat exchanger together. It was assumed the external flow circuit was ten feet long, and with the recommended line size for a Gerotor pump, the weight and volume of the transfer lines are:

$$\text{Weight of Hose and Fittings (lbs)} = .18 * \text{gal per min, and}$$

$$\text{Volume of Hose and Fittings } (FT^3) = .0032 * \text{gal per min.}$$

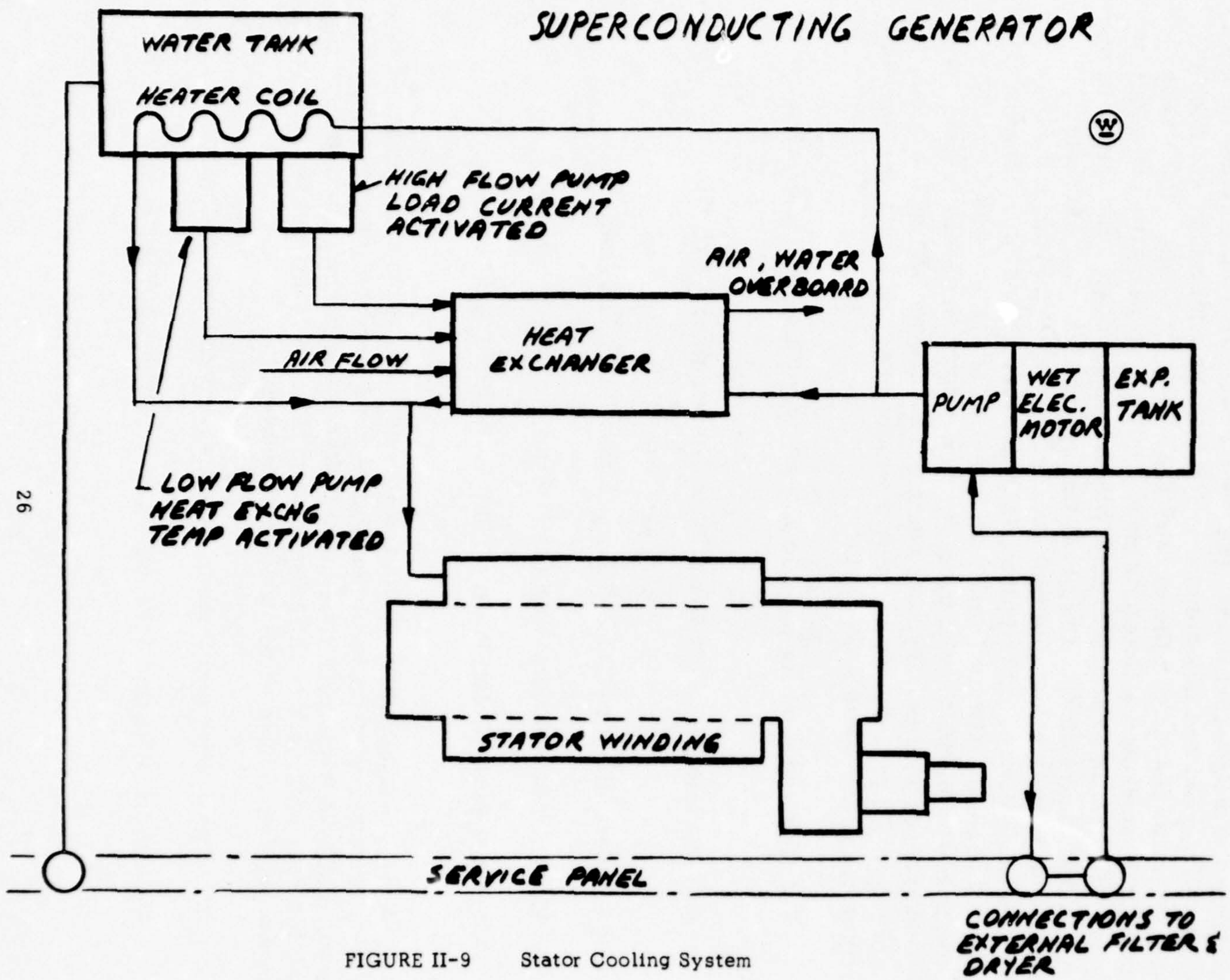


FIGURE II-9 Stator Cooling System

TABLE II-5

PARAMETERS FOR WET MOTOR/PUMP/TANK DESIGNS

Motor Output HP	RPM	Eff./pf	Weight, Lbs.	Pump Eff.	Δ PX Flow psi x GPM	Wt. of Element Lbs.
1.7	7500	70/ .77	1.45	60 %	30 x 58.28	2.5
5.0	7200	72.6/.818	6.25	60 %	30 x 171.4	9.96
7.5	7500	72.8/.827	7.35	60 %	30 x 257.1	14.33

Motor Output HP	Housing and Tank Lbs.	Total Wt. Lbs.	Volume In^3	Specific Volume In^3/gpm	Specific Weight (lbs/gpm)
1.7	2.85	6.45	174	2.99	.110
5.0	6.57	22.78	500	2.92	.133
7.5	9.39	31.07	8.7	3.18	.121

Generator Rating	Pump/Motor/Tank (Lbs.)	Pump/Motor/Tank In^3	GPM	ΔT °F
10 MVA	7.5	204	68.2	35
25 MVA - 4	14.4	323	108.	35
25 MVA - 6	21.5	473	162.	35
50 MVA - 4	26.7	700	220	35
50 MVA - 6	35.5	932	293	35

The approaches used for design of the heat exchanger for the transformer oil are:

- The surface areas of the heat exchanger shall be adequate to reject the No Load, 100% excitation losses under continuous operation with air flowing through the exchanger.

- Full load losses are removed by evaporation of an expendable liquid which is injected into the air stream.

- The air flow rate for the No Load, 100% excitation condition can be decreased if expendable liquid is injected into the air stream. This option will not change the weight and volume of the heat exchanger but only the required air flow.

Heat exchanger parameters are given in Table II-6 for sea level, hot day flight conditions. It can be noted from this table, the weight and volume of the heat exchanger for each design point are congruous with an airborne application. However, the air flow requirements impose an unusual demand upon the airborne cooling air system. For example, the air cooled generators (four) for the B52H aircraft require a total of 0.73 lbs/sec for the generators under similar flight conditions. Thus, the cooling air flow required by the point designs (Table II-6) is 1.6 to 5.6 times greater than the largest air cooled generator system in use today by the Air Force.

The Statement of Work defined the idle time and the number of cycles for each of the point designs. With a ten minute idle for each cycle, the total idle time per mission becomes:

Point Design Numbers	No. of Cycles per Mission	Total Idle Time, Min.
1 through 2	3	30
3	16	160
4	1	10
5 through 7	3	30
8	10	100

TABLE II-6

HEAT EXCHANGER PARAMETERS

Rating, MVA	10	25	25	50	50
Poles	4	4	6	4	6
Losses, No Load, Full Excitation, Btu/Sec	23.53	46.76	74.56	54.73	78.82
	SEA LEVEL, MACH 0.5				
Air Inlet Temperature (°F) Sea Level, Hot Day	128	128	128	128	128
Air Outlet Temperature (°F)	210	210	210	210	210
Air Flow Rate Lb/Sec	1.23	2.44	3.90	2.86	4.12
Required Surface on Air Side $In^2 \times 10^{-3}$	7.287	14.480	23.089	16.948	24.409
$\frac{\text{Area of Air Surface}}{\text{Area of Oil Surface}}$	8	8	8	8	8
Weight of Heat Exchanger Dry (lbs)	18.6	36.9	58.9	43.2	62.2
Volume of Heat Exchanger (In^3)	910	1760	2800	2060	2970
G (Air) $\frac{Lb}{In^2\text{-sec}}$	.1	.1	.1	.1	.1
G (Oil) $\frac{Lb}{In^2\text{-sec}}$	5	5	5	5	5
Average Oil Temperature (°F)	218	218	218	218	218

Weight of Heat Exchanger (Lbs) = No Load Stator Losses (KW) * .749

Volume of Heat Exchanger (FT^3) = No Load Stator Losses (KW) * .0206

Since the total idle time per mission is low, the use of an expendable coolant is an attractive option. Therefore, it was assumed that 75% of the no load, full excitation losses were absorbed by evaporation of water in the heat exchanger. The air flow required and the water consumption per mission for this case become:

No-Load Water Consumption (Lbs) = No Load Losses (KW) * Idle Time (Sec) * .75 * .0009624

Air Flow (Lbs/Sec) = No Load Losses (KW) * .25 * .04936

Full load stator losses are removed by evaporation of water in the heat exchanger also. Water consumption for the mode of operation becomes:

Full Load Water Consumption (Lbs) = Full Load Losses (KW) * On Time (Sec) * Cycles * .0009624

The water tank contains two constant displacement electric pumps. One of these pumps is load activated and injects water into the heat exchanger for removal of the full load losses. The other pump is activated by the temperature of the cooling oil and injects water into the heat exchanger for removal of the no-load, full excitation losses.

The configuration of the water tank was assumed to be an aluminum sphere with a wall thickness of 0.1 inches. The storage volume of the tank was increased by 20% to provide reserve capacity. Five pounds were added to the weight of the tanks to account for the weight of the electric pumps.

F. Helium Management

Cool-down of the cold structure in the rotor may require one to three and one-half hours as indicated in Table II-7. Therefore, the cool-down should be performed on the ground where the coolant is readily available via ground support equipment. Cool-down of the rotor can be accomplished by one of two methods. First, liquid helium can be circulated through the rotor by pressurization of a dewar on the ground. The transfer line would be connected to the rotor through a service panel on the airplane as shown in

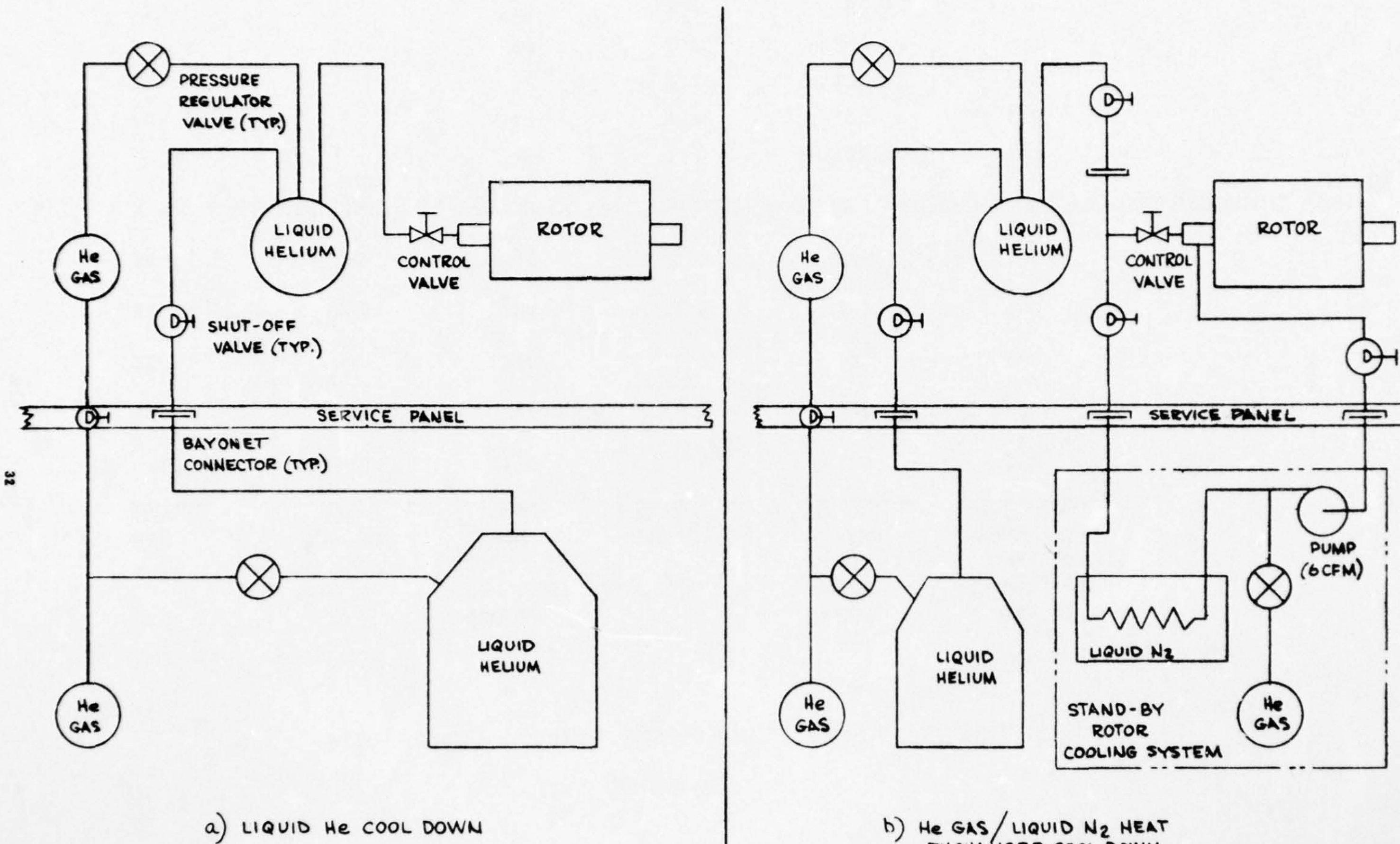
TABLE II-7

HELIUM REQUIREMENTS FOR LIQUID HELIUM COOL-DOWN (a)

Rating, MVA	Weight of 4.2K Structures, Lbs.	Helium Required for Cool-Down, Liters	Cool-Down Time, Hours	Helium Required for 10 Hours Mission, Liters	Weight of Dewar, and Helium On Board Aircraft, Lbs.
10	195	110	.9	150	350
25 - 4	318	177	1.2	170	400
25 - 6	442	246	1.7	170	400
50 - 4	599	334	2.2	200	450
50 - 6	789	440	2.9	200	450

HELIUM REQUIREMENTS FOR A COOL-DOWN WITH A HELIUM GAS TO LIQUID NITROGEN HEAT EXCHANGER (b)

Rating, MVA	Weight of 4.2K Structures, Lbs.	Helium Required for Cool-Down, Liters	Cool-Down Time, Hours	Helium Required for 10 Hours Mission, Liters	Weight of Dewar, and Helium On Board Aircraft, Lbs.
10		28	1.4	150	360
25 - 4		44	1.7	170	410
25 - 6		62	2.2	170	410
50 - 4		84	2.7	200	460
50 - 6		110	3.4	200	460



HELIUM MANAGEMENT

FIGURE II-10

Figure II-10a. All of helium used for cool-down would be vented overboard. The amount of helium required for cooling the rotor by this method is given in Table II-7a. Secondly, pressurized helium gas can be circulated through the rotor with a pump and subsequently cooled in a liquid nitrogen heat exchanger. The pump and heat exchanger would be part of the ground support equipment as shown in Figure II-10b.

Once the cold structure reached the temperature of liquid nitrogen (77K), liquid helium would be used for the remainder of the cool-down and vented overboard. The liquid helium required to cool the rotor from 77 to 4.2K would be approximately 25% of the amount required to make the entire cool-down with liquid helium.

After take-off, helium is consumed from the dewar aboard the airplane. The weight of the dewar and helium was based upon the mission time and the helium consumption rate. A consumption rate of:

$$\dot{V}\text{ (liter/hour)} = 1.5 * \text{MVA} * \left(\frac{10.}{\text{MVA}}\right)^{.82125}$$

was used to calculate the helium expended during a mission. The weight of the dewar and lines were calculated by:

$$\text{Weight of Dewar (Lbs)} = 2.35\ \frac{\text{Lbs}}{\text{Liter}} * \dot{V} * \text{Mission Time (Hours)}$$

G. Dimensions and Parameters for Various Generator Designs

The dimensions and other parameters of interest for the several generators are given in Tables II-8 through II-12. Table II-8 gives the voltage and reactances; Table II-9 gives the configuration of the armature windings and the field windings; Table II-10 and Table II-11 lists the dimensions and weights for the various components; breakdowns of the losses are summarized in Table II-12.

A weight summary for the generators with all ancillary equipment necessary to make them a functional unit for integration into complete power system is given in Table II-13. The design numbers given in this table represent the point design numbers of Table I-1.

TABLE II-8

POINT DESIGNS

VOLTAGE PARAMETERS AND REACTANCES

Rating, MVA	10	25	25	25	50	50	50
Power Factor, %	95	95	95	95	95	95	95
RPM	12647	8000	8000	8000	5656	5656	5656
Poles	4	4	4	6	4	6	4
Frequency, Hz	421.6	266.7	266.7	400	188.5	282.8	188.5
Voltages, Kv (dc)	60	60	200	60	200	200	60
L-L	47.8	47.8	159.4	47.8	159.4	159.4	47.8
L-N	27.6	27.6	92.0	27.6	92.0	92.0	27.6
Line Current, Amp	120.8	301.9	90.6	301.9	181.1	181.1	603.8
Voltage Regulation, %	13.87	8.65	10.2	11.99	8.64	10.22	13.70
Reactance, Per Unit							
Synchronous	.3156	.2150	.2455	.2807	.2150	.2466	.3125
Transient	.2673	.1446	.1927	.2394	.1383	.2010	.1803
Subtransient	.0735	.0486	.0981	.1253	.0483	.1317	.05

TABLE II-9

POINT DESIGNS

PARAMETERS FOR CONDUCTORS

Rating, MVA	10	25	25	25	50	50	50
Poles	4	4	4	6	4	6	4
KVDC	60	60	200	60	200	200	60
Armature Winding							
Connection	Y	Y	Y	Y	Y	Y	Y
Phase/Belts	3/60°	3/60°	3/60°	3/60°	3/60°	3/60°	3/60°
Turns Per Phase	280	180	600	189	460	462	192
Coil Pitch	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Total Conductor Length, Ft.	5,237	3,153	13,238	4,561	11,372	15,337	3,258
Current Density in Copper A/In^2	16,000	16,000	16,000	16,000	16,000	16,000	16,000
Strand Diameter, Mil	16.12	25.48	13.96	25.48	19.74	19.74	22.98
Number of Strands	37	37	37	37	37	37	91
Field Windings							
Number of Turns Per Pole	1150	1597	1689	1346	2211	1778	2094
Conductor Cross-Section, In^2	.00183	.00183	.00183	.00183	.00183	.00183	.00183
Total Conductor Length, Ft.	13027	19113	25405	30946	35098	51685	25142
Field Current, Amp	280	280	280	280	280	280	280
Max. Flux Density, tesla	4.61	4.66	4.64	4.67	4.68	4.59	4.66
Self Inductance, Henries	1.292	3.188	4.381	3.844	8.293	9.551	5.262
Field Energy, Kilojoules	50.6	125	172	150.7	325.1	374.4	206.3
Power Required for One Second Charge of Field, Kw	101.3	249.9	344	301.4	650.2	748.8	412.5

TABLE II-10

POINT DESIGNS

DIMENSIONS OF GENERATOR

Rating, MVA	10	25	25	25	50	50	50
Poles	4	4	4	6	4	6	4
KVDC	60	60	200	60	200	200	60
Dimensions, In.							
Frame, O.D.	20.3	28.8	32.2	25.4	43.0	37.9	39.4
Winding Return, O.D.	19.6	27.6	29.9	24.2	40.7	37.1	38.3
Iron Ring, O.D.	16.0	25.1	26.2	21.0	35.8	30.4	34.5
Iron Ring, I.D.	13.4	17.5	21.0	18.0	25.6	25.8	23.5
Active Winding, O.D.	13.0	17.1	19.4	17.6	24.0	24.2	23.1
Winding, I.D.	10.2	14.7	15.7	14.7	20.7	20.7	19.7
Bore Seal, I.D.	9.6	14.1	14.1	14.1	19.1	19.1	19.1
Rotor, O.D.	9.5	14.0	14.0	14.0	18.9	18.9	18.9
Cold Electro-Thermal Shield, O.D.	9.1	13.6	13.6	13.6	18.4	18.4	18.4
Field Container, O.D.	8.6	13.0	13.0	13.0	18.0	18.0	18.0
Field Winding, O.D.	7.6	12.0	12.0	12.0	17.0	17.0	17.0
Field Winding, I.D.	3.6	9.0	8.8	8.0	14.2	13.6	14.2
Active Length	12.8	10.1	14.8	18.0	12.1	21.4	6.3
Bearing to Bearing Length	31.1	29.1	36.8	37.0	36.6	44.2	29.2
Overall Length	47.1	45.1	52.8	53.0	45.2	60.2	45.2
Volume of Generator, Ft^3	4.82	8.52	13.2	9.28	24.8	24.7	15.8
L/D=Brg to Brg Length/Rotor OD	3.27	2.08	2.63	2.64	1.94	2.34	1.54

TABLE II-11

WEIGHTS FOR POINT DESIGNS

Rating, MVA	10	25	25	25	50	50	50
Poles	4	4	4	6	4	6	4
Voltage, KVDC	60	60	200	60	200	200	60
Weight, Lbs.							
Stator							
Copper	153	229	289	331	496	669	474
Magnetic Iron	243	691	864	497	1854	1297	1050
Insulation	105	153	652	223	866	1042	175
Armature Frame	101	138	182	143	309	274	219
Bearing Brushes, Etc.	30	34	34	34	38	38	38
	632	1245	2021	1228	3563	3320	1956
Rotor							
Cold Structure (4.3 K)							
Superconducting Wire	83	122	162	197	223	329	160
Copper Heat Exchanger	12	14	20	21	29	37	19
Wire Insulation	7	11	13	16	20	30	16
Bulk Insulation	16	44	55	37	100	117	82
Coil Supports, Ends	8	12	12	13	23	22	26
Container	69	115	146	158	204	254	157
	195	318	408	442	599	789	460
Cold Electro-Thermal Shield	38	62	75	75	94	115	73
Warm Electrical Shield	48	64	76	91	123	150	115
Anti-Drive End Shaft	26	41	41	41	58	58	58
Drive End Shaft	34	52	52	52	74	74	74
Power Leads, Helium Transfer	12	12	12	12	12	12	12
	158	231	256	271	361	409	332
Generator Total	983	1794	2685	1941	4523	4518	2748
Generator Specific Weight #/KVA	.0985	.0718	.1074	.0776	.0905	.0904	.0550

TABLE II-12

LOSSES IN POINT DESIGNS

Rating, MVA	10	25	25	25	50	50	50
Poles	4	4	4	6	4	6	4
KVDC	60	60	200	60	200	200	60
Losses, KW							
No Load and No Excitation							
(Sea Level) Windage	2.16	2.06	2.35	2.51	2.69	3.24	2.98
Brush Friction	.80	.53	.53	.53	.34	.34	.34
Bearing Friction	2.64	1.72	1.72	1.72	1.28	1.28	1.28
Total	5.60	4.31	4.60	4.76	4.31	4.86	4.60
No Load with 100% Excitation							
Friction and Windage	5.60	4.31	4.60	4.76	4.31	4.86	4.60
Iron Losses	19.03	21.37	32.50	35.80	40.05	53.57	22.69
Eddy Currents, Losses	5.79	27.95	5.67	42.85	17.68	29.57	28.31
Total	30.42	53.63	42.77	83.41	62.04	88.00	55.60
Full Load Losses							
Full Excitation Losses	30.42	53.63	42.77	83.41	62.04	88.00	55.60
Load Losses I^2R	101.28	152.46	197.30	218.06	338.95	457.14	323.75
Eddy Currents Due to Rectified Load	14.88	22.68	18.06	20.40	34.88	33.96	90.72
Total	146.58	228.77	258.13	321.87	435.87	579.10	470.07
Power Required by Lube Pump	.19	.19	.19	.19	.19	.19	.19
Clutch Friction	6.71	16.77	16.77	16.77	33.55	33.55	33.55

TABLE II-13

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

SUPERCONDUCTING GENERATOR

SUMMARY OF WEIGHTS

POINT DESIGN NUMBER	1, 2	4	8
MVA	10	25	50
GENERATOR, LBS.	983	1940	4403
GEAR BOX	20	20	20
LUBE PUMP	5	5	5
LUBE FITTINGS AND LINES	17	17	17
LUBE HEAT EXCHANGER	12	12	12
HYDRAULIC MOTOR	12	31	38
PUMP/MOTOR/TANK	9	19	35
HEAT EXCHANGER	19	59	62
HOSE/FITTINGS	12	27	48
EXCITATION EQUIPMENT	32	40	53
FIXED WEIGHT	1121	2170	4693
EXPENDABLES & TANKS			
HELIUM, 10 HOUR MISSION	41	49	55
DEWAR	104	118	129
WATER, 30 MIN. IDLE	32	102	108
WATER, FULL LOAD	9 (63 Sec)	37 (120 Sec)	66 (120 Sec)
WATER TANK AND PUMPS	11	19	21
	197	325	379
TOTAL	1318	2495	5072
SPECIFIC WEIGHT (LBS/KVA)	.132	.0998	.101

TABLE II-14

PARAMETERS FOR 25 MVA, 60 KVDC, 6800 RPM GENERATOR
6-POLES, 340 HZ

VOLTAGE AND REACTANCES	
Voltages, Kv	60 d.c.
L-L	47.8
L-N	27.6
Line Current, Amp	301.9
Voltage Regulation, %	15.00
Volts/Turn	95.95
Reactance, Per Unit	
Synchronous, Open Circuit	.2921
Full Load	.3359
Transient	.2711
Subtransient	.0869
STATOR DIMENSIONS, IN.	
Frame, O.D.	39.3
Winding Return, O.D.	28.1
Iron Ring, O.D.	24.5
Iron Ring, I.D.	20.4
Active Winding, O.D.	20.0
Winding, I.D.	16.8
Bore Seal, I.D.	16.2
Overall Length	44.6

ARMATURE WINDING	
Type	Gramme
Connection	Y
Phase/Belts	3/60°
Turns Per Phase	288
Coil Pitch	1.0
Total Conductor Length, Ft.	4521
Current Density in Copper A/In^2	16,000
Strand Diameter, Mil	25.48
Number of Strands	37
FIELD WINDINGS	
Number of Turns per Pole	2279
Conductor Cross Section, In.^{2}	.00183
Total Conductor Length, Ft.	22,442
Field Current, Amp	280
Max. Flux Density, tesla	4.66
Self Inductance, Henries	3.045
Field Energy, Kilojoules	119.4
Power Required for One Second Charge of Field, Kw	238.7
ROTOR DIMENSIONS, IN.	
Rotor, O.D.	16.1
Cold Electric Shield, O.D.	15.6
Field Container, O.D.	15.2
Field Winding, O.D.	14.2
Field Winding, I.D.	8.0
Active Length	8.6
Bearing to Bearing Length	28.6

TABLE II-15

PARAMETERS FOR 25 MVA, 60 KVDC, 6800 RPM GENERATOR

6-POLE, 340 HZ

Weight, Lbs.		Losses, KW	
Stator		**No Load and No Excitation**	
Copper	329	(Sea Level) Windage	2.30
Magnetic Iron	395	Brush Friction	.45
Insulation	172	Bearing Friction	1.75
Armature Frame	144		4.5
Bearing Brushes, Etc.	34		
	1074	**No Load with 100% Excitation**	
		Friction and Windage	4.50
Rotor		Iron Losses	21.90
Cold Structure (4.2K)		Eddy Currents, Losses	38.15
Superconducting Wire	143		64.55
Copper Heat Exchanger	20		
Wire Insulation	11	**Full Load Losses**	
Bulk Insulation	42	Full Excitation Losses	64.55
Coil Supports, Ends	16	Load Losses I^2R	218.11
Container	122	Eddy Currents Due to Rectified Load	28.50
	354		311.16
Cold Electro-Thermal Shield	63		
Warm Electrical Shield	84		
Anti Drive End Shaft	36		
Drive End Shaft	66	Power Required by Lube Pump	.19
Power Leads, Helium Transfer	12		
	261		
		Clutch Friction	16.77
Generator Total	1689		
Generator Specific Weight #/KVA	.0676		

TABLE II-16

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION

WEIGHT SUMMARY

25 MVA, 6800 RPM, 60 KVDC

GENERATOR	1689 LBS.
GEAR BOX	20
LUBE PUMP	5
LUBE FITTINGS/LINES	17
LUBE HEAT EXCHANGER	12
HYDRAULIC MOTOR	24
PUMP/MOTOR/TANK	18
HEAT EXCHANGER	50
HOSE/FITTINGS	25
EXCITATION EQUIPMENT	40
FIXED WEIGHT	1899
EXPENDABLES AND TANKS	
HELIUM, 10 HOUR MISSION	49
DEWAR	118
WATER, 30 MIN. IDLE	78
WATER, FULL LOAD	34
WATER TANK AND PUMPS	17
	296
TOTAL	2195
SPECIFIC WEIGHT (LBS/KVA)	.0878

TABLE II-17

SPECIFIC WEIGHT OF 6800 RPM, 6-POLE GENERATORS AND SUBSYSTEMS

MVA	MW	KVDC	WEIGHT OF GENERATOR, LBS.	LBS/KVA
		25	1360	.0518
26.316	25	30	1395	.0530
		35	1425	.0511
		25	1570	.0498
31.579	30	30	1595	.0505
		35	1640	.0519
		25	1795	.0487
36.842	35	30	1810	.0492
		35	1825	.0496

FOR ON TIME 120 SEC., IDLE TIME 30 MIN., COLD TIME 10 HOURS

MVA	MW	KVDC	WEIGHT OF COMPLETE SUBSYSTEM	LBS/KVA
		25	2020	.0768
26.316	25	30	2055	.0780
		35	2085	.0792
		25	2205	.0699
31.579	30	30	2230	.0706
		35	2275	.0720
		25	2495	.0677
36.842	35	30	2510	.0682
		35	2575	.0699

During the final phase of this study, it was learned that a 6800 RPM turbine is being considered as a subsystem for a power level of approximately 25 MW. Since this study was based upon 8000 RPM as the rotor speed for a 25 MVA power level, it was decided to investigate the impact of this new rotor speed upon the generator to assure compatibility of these subsystems without a speed changer.

Tables II-14 and II-15 present the parameters of interest for a 25 MVA, 60 KVDC, 6800 RPM, 6-pole generator. A weight summary for this generator with all ancillary equipment necessary to make it a functional unit for integration with a 6800 RPM turbine is given in Table II-16. Comparable values of generator and system weight at lower voltages (25 to 35 kVDC) and at slightly higher outputs (25 to 30 MW) are summarized in Table II-17.

H. Superconducting Generator Computer Code

The object of the computer code is to provide the Air Force with a method of computing weights and volumes of superconducting high power generating systems and to list the auxiliary requirements of the system on the aircraft which employs the system. The input variables allow the user to input any point design in the range of Table I-1, and receive as output the weight, volume, and auxiliary requirements of the specified machines.

The computer code is the result of several complete designs for superconducting subsystems. Designs were made at several power and voltage levels with both four and six poles. The code was developed from these point designs. The values given in the output of the code are considered to be within 10% of those of an actual system.

SUPERCONDUCTING GENERATOR

COMPUTER CODE

INPUT SHEET

The following parameters must be input to the Westinghouse Superconducting Generator Computer Code. They are read in on two Data Cards in F10.4 Formats.

Card 1

Parameter	Columns	Units	Range	Sample
POWER	1-10	MW	10-56	25.
VOLTAGE*	11-20	KVDC	20-200	60.
POWER FACTOR	21-30		.9-1.0	1.0
POLES	31-40		4 or 6	6.
ON TIME	41-50	Seconds	0-99,999	120.
CYCLES	51-60		0-99,999	1.
IDLE TIME	61-70	Minutes	0-99,999	10.

Card 2

Parameter	Columns	Units	Range	Sample
COLD TIME	1-10	Hours	0-99,999	10.

NOTE: A decimal point must appear in each Input Format Space.

* The AC Output Voltage is assumed to be rectified to DC, hence the DC units; the weights and volumes do not include the rectifier.

	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80
CARD 1	POWER	VOLTAGE	POWER FACTOR	POLES	ON TIME	CYCLES	IDLE TIME	
CARD 2	COLD TIME							

SUPERCONDUCTING GENERATOR

COMPUTER CODE

INPUT VARIABLE DEFINITION

POWER	-	The megawatt output of the machine.
VOLTAGE	-	The DC voltage the machine is intended to produce in KVDC. KVDC = 2.17 KVAC (L-N).
POWER FACTOR	-	The power factor of the load for the AC machine.
ON TIME	-	The full-load time on the machine per cycle in seconds.
POLES	-	The number of poles on the machine. Must be 4 or 6.
CYCLES	-	The number of cycles per mission.
IDLE TIME	-	The time in minutes the machine is to be fully excited at rated RPM No Power Output.
COLD TIME	-	The time in hours the machine is expected to maintain Superconducting Temperature independent of Ground Support Equipment.

SUPERCONDUCTING GENERATOR

COMPUTER CODE

OUTPUT VARIABLE DEFINITIONS

COMPONENTS (See Generator Drawing and Schematics)

Generator	-	All components of generator including bearings, brushes, slip rings, and helium transfer seals.
Gear Box	-	The gears and box and input pad for hydraulic motor.
Lube Pump	-	Lube pump and scavenge elements for lubrication system.
Lube Fittings-Valves-Lines	-	Lubrication system components.
Lube Heat Exchanger	-	Heat exchanger for lubrication system.
Hydraulic Motor	-	Hydraulic motor served from aircraft hydraulic system to spin rotor at rated speed during idle time, and drives lube system.
T-Oil Motor-Pump-Tank	-	Transformer oil motor pump and tank. This is a single sealed unit and is part of the high voltage stator cooling system.
T-Oil Fittings-Hose	-	Stator cooling system components.
T-Oil Heat-Exchanger	-	Stator cooling system components.
Excitation Power Equipment	-	Power conditioning equipment to convert aircraft power to excitation power for the field.
Total Fixed Weight & Volume	-	The total fixed weight and volume not including expendables and tanks for expendables.

Liquid Helium	-	Coolant for the field coil.
Dewar	-	Tank to hold helium.
Water, Full Load	-	Water to be evaporated by heat exchanger during full-load operation.
Water, No Load	-	Water to be evaporated by heat exchanger during no-load, full excitation conditions.
Water Tanks & Pumps	-	Components of cooling system.
Total	-	The total weight and volume of the power generating subsystem.

<u>DIMENSIONS OF GENERATOR</u> (See Generator Drawing)

Diameter of Frame	-	Outside diameter of generator.
Bearing to Bearing Dis	-	Shown on drawing.
Overall Length	-	Length of frame

<u>REQUIREMENTS ON AIRCRAFT SYSTEM</u>

Hydraulic Fluid	-	Hydraulic fluid to run hydraulic motor during idle time.
Excitation Power	-	Power required from aircraft to excite field winding in one minute.
Power for Pumps	-	Power required from aircraft to run coolant pumps.
Air Flow	-	Air needed to pass over heat exchanger during idle time and full load conditions.

MISCELLANEOUS DATA

Power Output	- Rated output of machine.
Poles	- The number of poles.
Frequency	- The frequency of the output of the machine.
Power Required from Turbine	- Input shaft power.
Rotor Weight	- The weight of the rotor.
Cold Structure Weight	- The weight of all components that must be cooled to $4.2^{o}K$
Rotor Speed	- The RPM of the machine
Rotor Diameter	- Outside diameter of rotor.
Rotor Moment of Inertia	- Rotor inertia.
Full Load Stator Loss	- Stator loss at full-load.
Full Excitation No Load Stator Loss	- Stator loss at idle conditions.
Liquid Helium Required to Cool from Room Temperature	Helium required to lower field temperature to superconducting state from room temperature.
Liquid Helium Required to Cool Rotor from Liquid Nitrogen Temperature	Helium required to lower field temperature if liquid nitrogen is used for initial cool down.
Load on Hydraulic Motor	- The machine losses which must be overcome by hydraulic motor during idle time.

SUPERCONDUCTING GENERATOR

COMPUTER CODE VARIABLE DEFINITION

USER DEFINED VARIABLES	DEFINITION	UNITS
P	Power	MW
V	Voltage	KVDC
PF	Power Factor	-
PL	Poles	-
ON	On Time Per Cycle	SEC
CYCLES	Cycles	-
XIDLE	Time at Idle	MIN
COLD	Time at $4.2^{o}K$	HOURS

COMPUTED VARIABLES	DEFINITION	UNITS
M	MVA	MVA
WG	Weight of Generator	LBS
FLSL	Full Load Stator Loss	KW
LHM	Load on Hydraulic Motor	KW
NLSL	No Load Stator Loss	KW
PRFT	Power Required from Turbine	MW
VOLG	Volume of Generator	FT^3
DOF	Diameter of Frame	INCHES
BTBL	Bearing to Bearing Length	INCHES
OAL	Overall Length	INCHES
CSW	Cold Structure Weight	LBS
RWT	Rotor Weights	LBS
WGM	Metric Generator Weight	KG
VOLGM	Metric Generator Volume	M^3
WGB	Weight Gear Box	LBS
WGBM	Weight Gear Box Metric	KG
VGB	Volume Gear Box	FT^3

COMPUTED VARIABLES	DEFINITION	UNITS
VGBM	Volume Gear Box Metric	M^3
WLP	Weight Lube Pumps	LBS
WLPM	Weight Lube Pumps Metric	KG
VLP	Volume Lube Pumps	FT^3
VLPM	Volume Lube Pumps Metric	M^3
WLFL	Weight Lube Fittings & Lines	LBS
WLFLM	Weight Lube Fittings & Lines Metric	KG
VLFL	Volume Lube Fittings & Lines	FT^3
VLFLM	Volume Lube Fittings & Lines Metric	M^3
WLHE	Weight Heat Exchanger	LBS
WLHEM	Weight Heat Exchanger Metric	KG
VLHE	Volume Heat Exchanger	FT^3
VLHEM	Volume Heat Exchanger Metric	M^3
WHM	Weight Hydraulic Motor	LBS
WHMM	Weight Hydraulic Motor Metric	KG
VHM	Volume Hydraulic Motor	FT^3
VHMM	Volume Hydraulic Motor Metric	M^3
GPM	Transformer Oil Flow	GPM
WPMT	Weight Coolant Pump Rotor & Tank	LBS
WPMTM	Weight Coolant Pump Rotor & Tank Metric	KG
VPMT	Volume Coolant Pump Motor & Tank	FT^3
VPMTM	Volume Coolant Pump Motor & Tank Metric	M^3
WTHF	Weight of Transformer Oil Hoses and Fittings	LBS
WTHFM	Wt. of Transformer Oil Hoses & Fit'gs Metric	KG
VTHF	Volume of Trans. Oil Hoses & Fittings	FT^3
VTHFM	Vol. of Trans. Oil Hoses & Fittings Metric	M^3
WSHE	Weight Stator Heat Exchanger	LBS
WSHEM	Weight Stator Heat Exchanger Metric	KG
VSHE	Volume Stator Heat Exchanger	FT^3
VSHEM	Volume Stator Heat Exchanger Metric	M^3
WEPS	Weight Excitation Power Supply	LBS
WEPSM	Weight Excitation Power Supply Metric	KG
VEPS	Volume Excitation Power Supply	FT^3
VEPSM	Volume Excitation Power Supply Metric	M^3
FW	Fixed Weight	LBS
FWM	Fixed Weight Metric	KG
FV	Fixed Volume	FT^3
FVM	Fixed Volume Metric	M^3

COMPUTED VARIABLES	DEFINITION	UNITS
WHEL	Weight of Helium	LBS
WHELM	Weight of Helium Metric	KG
VHEL	Volume of Helium	FT^3
VHELM	Volume of Helium Metric	M^3
WOD	Weight of Dewar	LBS
WODM	Weight of Dewar Metric	KG
VOD	Volume of Dewar	FT^3
VODM	Volume of Dewar Metric	M^3
WWFL	Weight Water Full Load	LBS
WWFLM	Weight Water Full Load Metric	KG
VWFL	Volume Water Full Load	FT^3
VWFLM	Volume Water Full Load Metric	M^3
WWNL	Weight Water No Load	LBS
WWNLM	Weight Water No Load Metric	M^3
VW	Total Volume Water	FT^3
D1	Inside Diameter Helium Tank	FT
D2	Outside Diameter Helium Tank	FT
D3	Inside Diameter Water Tank	FT
D4	Outside Diameter Water Tank	FT
WWTP	Weight Water Tank & Pump	LBS
WWTPM	Weight Water Tank & Pump Metric	KG
VWTP	Volume Water Tank & Pump	FT^3
VWTPM	Volume Water Tank & Pump Metric	M^3
TW	Total Weight	LBS
TWM	Total Weight Metric	KG
TV	Total Volume	FT^3
TVM	Total Volume Metric	M^3
DOFM	Diameter of Frame Metric	M
BTBLM	Bearing to Bearing Length Metric	M
OALM	Overall Length Metric	M
HGPM	Hydraulic Fluid Flow	GPM
RFP	Required Field Power	KW
AIRF	Air Flow	LBS/SEC
FREQ	Frequency	HERTZ
RPM	Rotor Speed	RPM
ROTD	Rotor Diameter	FT
RMI	Rotor Moment of Inertia	LB IN SEC^2
VHFCD	Volume Helium for Cooling from room temp	LITERS
VHFLN	Vol. Helium for Cooling from liquid nitrogen temp	LITERS
XHFP	Hydraulic Fluid Pressure	PSI

SUPERCONDUCTING GENERATOR

COMPUTER CODE

DERIVATION OF EQUATIONS

The computer code for the Superconducting Generator is centered around seven base designs. Machines were designed to operate at 20, 60, 200 KVDC and at 10, 25, 50 MVA. The base designs were used to formulate curves representing machine characteristics throughout the power and voltage range requested.

The desired voltage and power level is input into the program along with duty cycle information and the number of poles. The first part of the program is a decision making process. The program either finds the base design for the machine most similar to the input values or prints a statement saying that the machine is impractical (see section on limits of applicability).

Using the appropriate base design as a reference, values for machine parameters such as weight, losses, length, diameter etc. are computed. The parameters for the base design are adjusted according to empirical formulas to represent the desired machine which was input by the user. For example, if a 21 MVA, 40 KVDC, 6 pole machine was desired, the program would branch to the section containing the parameters for a 25 MVA, 60 KVDC, 6 pole machine. Then the parameters of the base machine would be adjusted to represent the desired machine.

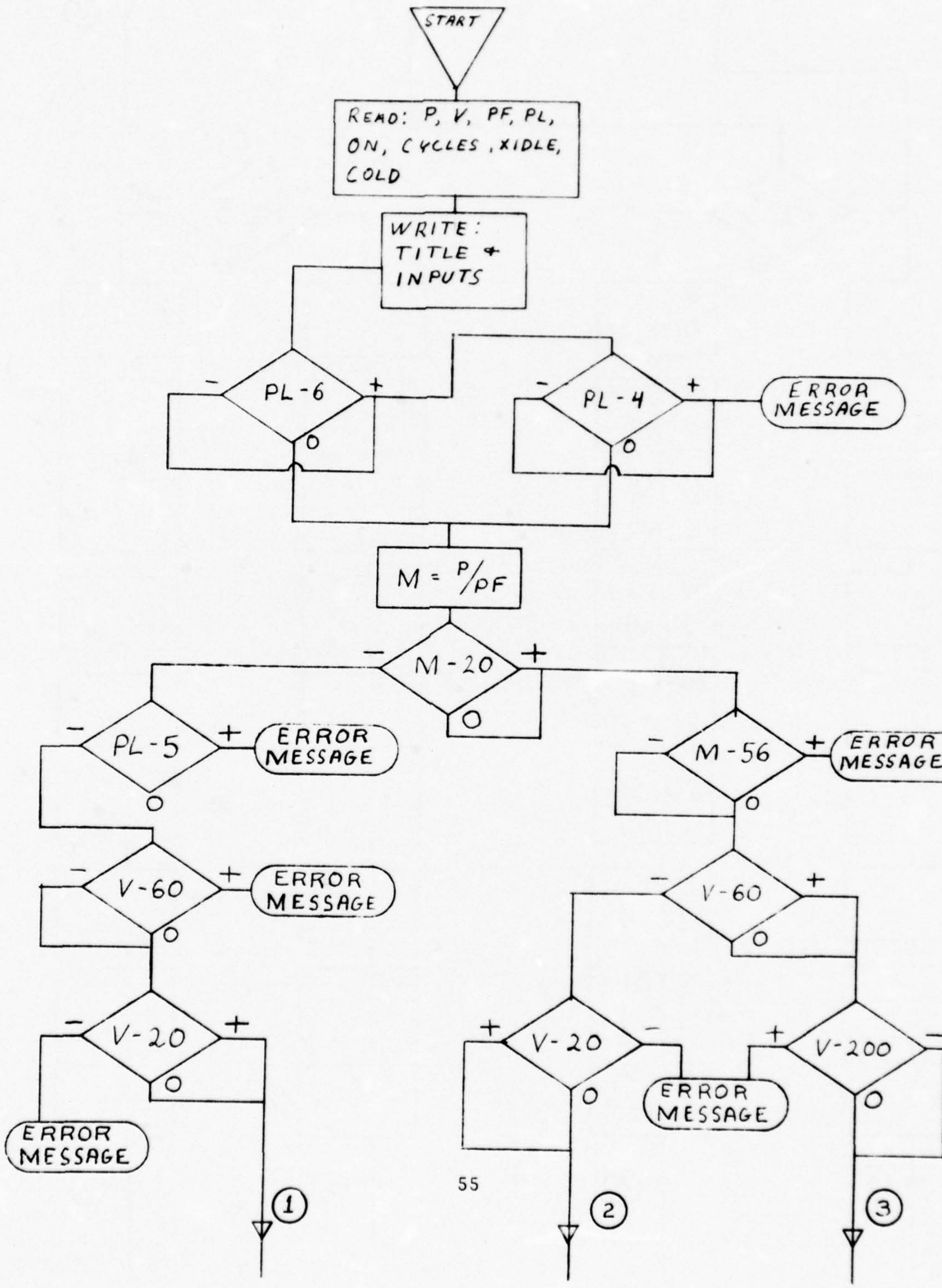
After the parameters of the specific machines have been calculated, the program calculates parameters that are common to all machines such as requirements on the aircraft. Also, English values are converted to metric values so that both units can be printed out.

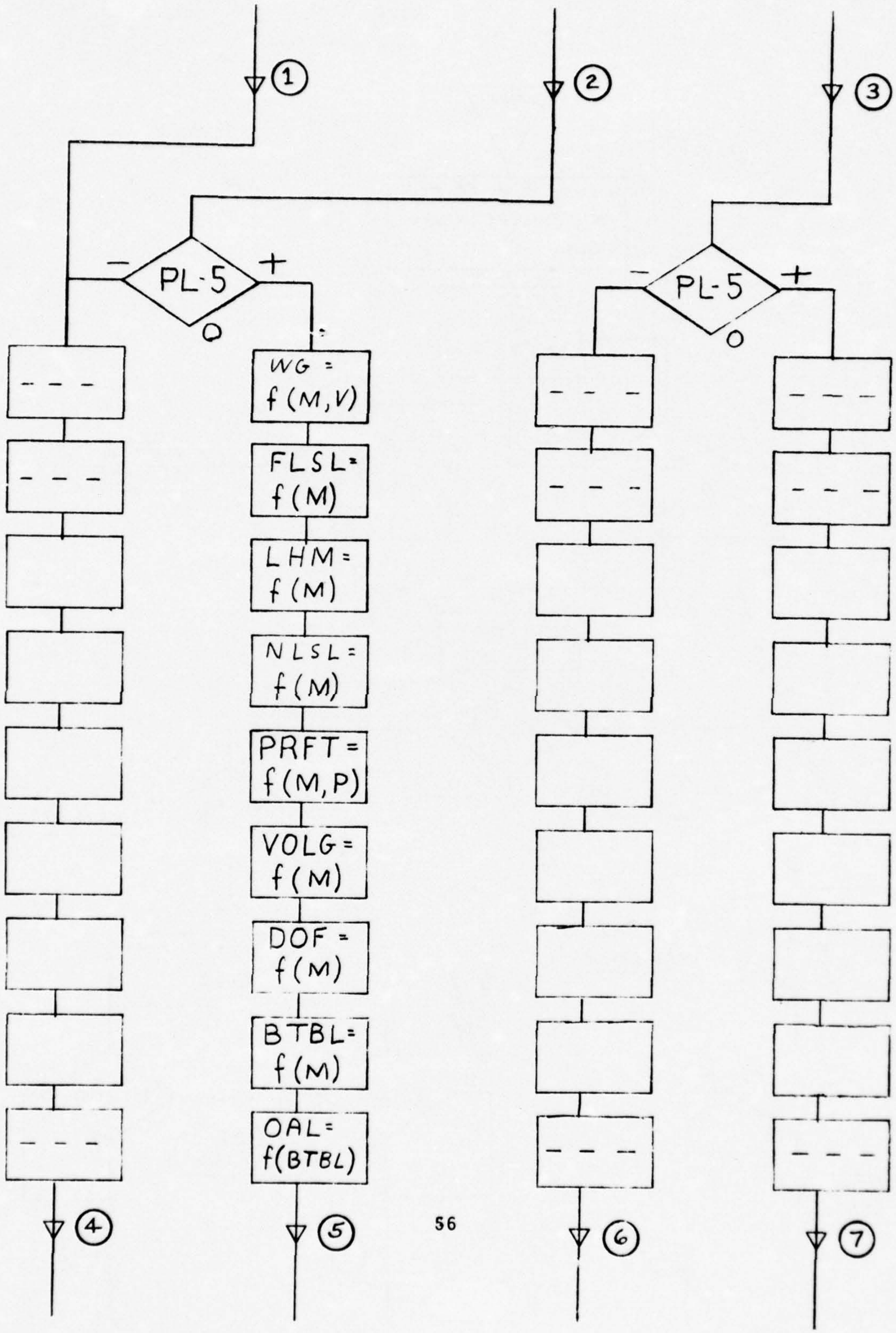
Three tables are printed out including 1) weights and volumes, 2) dimensions and requirements on the aircraft, 3) miscellaneous data.

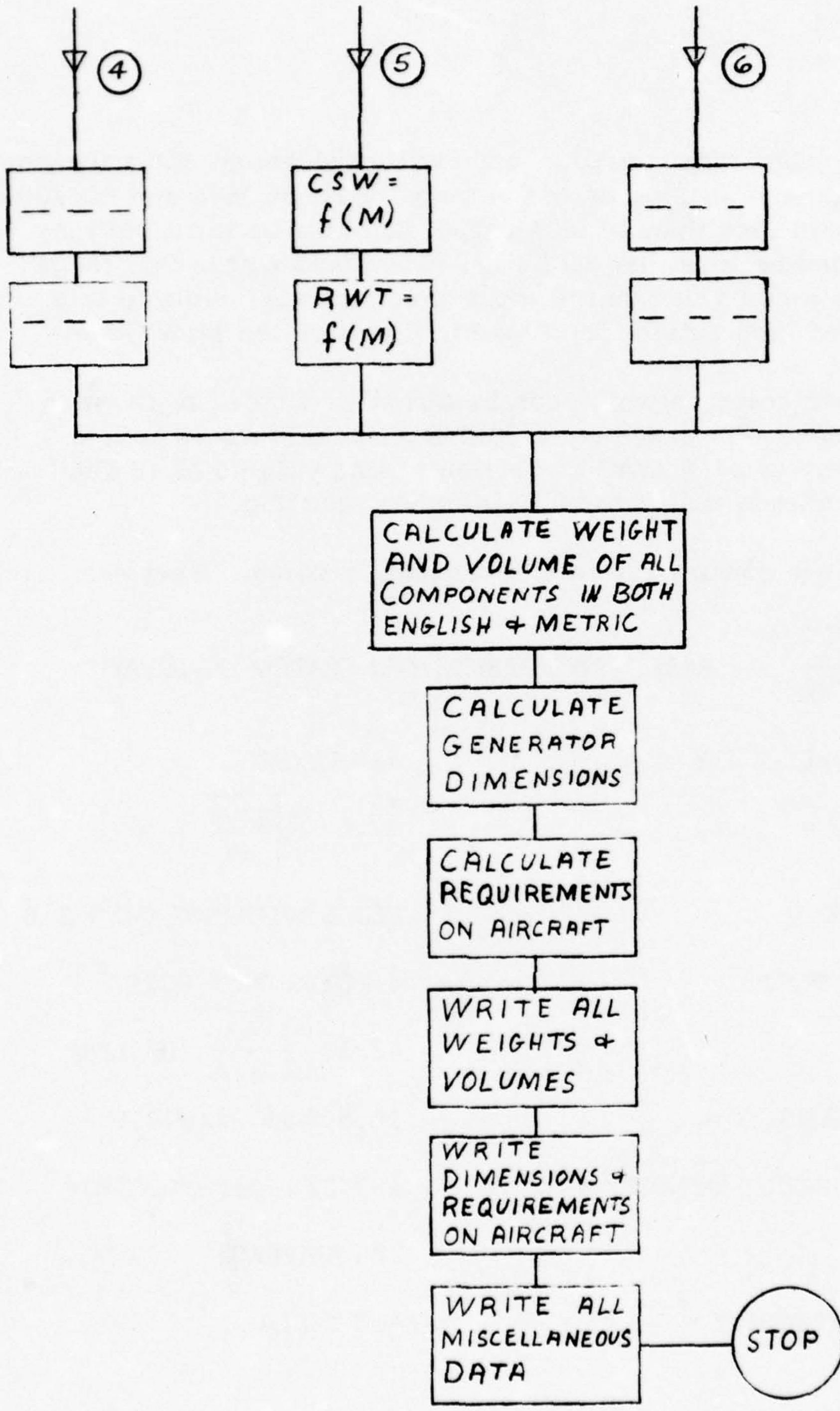
SUPERCONDUCTING GENERATOR

COMPUTER CODE

FLOW DIAGRAM


START
READ: P, V, PF, PL, ON, CYCLES, XIDLE, COLD
WRITE: TITLE + INPUTS
PL-6
PL-4
ERROR MESSAGE
M = P/PF
M-20
PL-5
ERROR MESSAGE
M-56
ERROR MESSAGE
V-60
ERROR MESSAGE
V-60
V-20
ERROR MESSAGE
V-20
ERROR MESSAGE
V-200
1
2
3


1
2
3
PL-5
+
−
0
PL-5
+
−
0
WG = f(M,V)
FLSL= f(M)
LHM = f(M)
NLSL = f(M)
PRFT = f(M,P)
VOLG = f(M)
DOF = f(M)
BTBL= f(M)
OAL= f(BTBL)
4
5
6
7


4
5
6
7
CSW = f(M)
RWT = f(M)
CALCULATE WEIGHT AND VOLUME OF ALL COMPONENTS IN BOTH ENGLISH & METRIC
CALCULATE GENERATOR DIMENSIONS
CALCULATE REQUIREMENTS ON AIRCRAFT
WRITE ALL WEIGHTS & VOLUMES
WRITE DIMENSIONS & REQUIREMENTS ON AIRCRAFT
WRITE ALL MISCELLANEOUS DATA
STOP

SUPERCONDUCTING GENERATOR

COMPUTER CODE

LIMITS OF APPLICABILITY

The Superconducting Generator computer code will give weight and volumes for machines with either 4 or 6 poles in the range of 20-56 MVA and 20-200 KVDC. Machines with less than 20 MVA output can also be input but they must have 4 poles and be less than 60 KVDC. Machines within this range and within the input range given on the input sheet are applicable to this computer code. Machines outside the range will produce an Error Code.

The machines produce voltages which can be directly rectified to DC with no step-up transformer. For example, a 60 KVDC machine would have a line to neutral voltage of 27.6 KVAC and a line to line voltage of 48 KVAC. The line to neutral voltage will give 60 KVDC when rectified.

Certain parameters are constrained by the computer program. They are:

$\text{RPM} = 5656 \sqrt{\frac{50}{\text{MVA}}}$ BASED ON TURBINE-GENERATOR INTERFACE.

ROTOR PERIPHERAL VELOCITY =	420 FT/SEC
FIELD WINDING OD =	$17.0 \sqrt{\frac{\text{MVA}}{50}}$
STATOR WINDING ID =	FIELD WINDING OD + 2.6
NUMBER OF ROTOR POLES	4 POLES OR 6 POLES
FREQUENCY =	$47.13 \sqrt{\frac{50}{\text{MVA}}}$ (POLES)
STATOR CURRENT DENSITY =	16,000 AMPS/(INCH)^2
FIELD WINDING CURRENT DENSITY =	153,228 AMPS/(INCH)^2
FIELD CURRENT =	280 AMPERES
MAXIMUM FIELD INTENSITY =	4.6 TESLA

APPENDIX 1

SUPERCONDUCTING GENERATOR COMPUTER CODE

LISTING AND SAMPLE OUTPUT

```
DOS FORTRAN IV 360N-FO-479 3-3          MAINPGM          DATE   01/20/76      TIME    15.05.21

              REAL LHM1
              REAL LHM2
              REAL LHM
              REAL NLSL1
              REAL NLSL2
              REAL NLSL
              REAL M
        777   READ(1,5)P,V,PF,PL,ON,CYCLES,XIDLE,CCLD
        5     FORMAT(7F10.4/F10.4)
              WRITE(3,3)
        3     FORMAT('1 SUPERCONDUCTING GENERATOR, WESTINGHOUSE ELECTRIC CORP.')
              WRITE(3,1)
        1     FORMAT(/,3X' POWER      VOLTAGE       PF          POLES     ON TIME     CYC
             1LES      XIDLE        CCLD  '/
             1         4X,   'MW          KV                              SEC
             1            MIN         HOURS'/)
              WRITE(3,2)P,V,PF,PL,ON,CYCLES,XIDLE,CCLD
        2     FORMAT(1X,3F10.4,/////)
              IF(PL-6.)10,20,10
        10    IF(PL-4.)15,20,15
        15    WRITE(3,16)
        16    FORMAT(1X,'INCORRECT NUMBER OF POLES')
        17    GO TO 500
        20    M=P/PF
        25    IF(M-20)30,100,100
        30    IF(PL-5)40,15,35
        35    WRITE(3,18)
        18    FORMAT(1X,'INCORRECT NUMBER OF POLES FOR MVA LESS THAN 20.')
              GO TO 500
        40    IF(V-60.)45,45,50
        50    WRITE(3,51)
        51    FORMAT(1X,'INCORRECT VOLTAGE AT 4 POLES AND LESS THAN 20 MVA')
              GO TO 500
        45    IF(V-20)60,55,55
        60    WRITE(3,61)
        61    FORMAT(1X,'INCORRECT VOLTAGE')
              GO TO 500
        100   IF(M-56)110,110,105
        105   WRITE(3,106)
        106   FORMAT(1X' POWER IS GREATER THAN 56 MW')
              GO TO 500
        110   IF(V-60)115,125,125
        115   IF(V-20)60,120,120
        120   IF(PL-5.)55,15,140
        125   IF(V-200)135,135,130
        130   WRITE(3,131)
        131   FORMAT(1X,'VOLTAGE IS GREATER THAN 200 KVDC')
              GO TO 500
        135   IF(PL-5)145,15,150
        C
        C     20 KVDC LESS THAN VOLTAGE LESS THAN 60 KVDC
        C     MVA LESS THAN 20
        C     POLES = 4
        C
        55    SW1=071.8*((25./M)**.345)
              SW2=SW1*(1.-.06*(60.-V)/40.)
              WG=M*SW2
              FLSL=M*14.098*((10./M)**.49243)
```

```
0051          LHM=3.1625*M*((10./M)**.37883)+.699*M+.2
0052          NLSL=2.482*M*((10./M)**.25059)
0053          PRFT=M*.0046464*((M/10)**.44813 )+P
0054          VCLG=.4315*M*((10./M)**.37182)
0055          DCF=M*2.034*((10./M)**.6183)
0056          BTBL=M*3.11*((10./M)**1.0725)
0057          CAL=BTBL+16.
0058          CSW=19.5*M*(10./M)**.46627
0059          RWT=35.3*M*(10./M)**.518023
0060          GO TO 400
        C
        C     20 KVDC LESS THAN VOLTAGE LESS THAN 60 KVDC
        C     POLES = 6
        C     MVA GREATER THAN 20
        C
0061    140   SW1=C77.6*((25./M   )**.4966)
0062          SW2=SW1*(1.-.06*(60.-V)/140.)
0063          WG=M*SW2
0064          FLSL=M   *12.684
0065          LHM=4.174*M+.2
0066          NLSL=3.146*M
0067          PRFT=M*.009533+P
0068          VCLG=M*.37136
0069          DCF=M*1.016*((25./M)**.5666)
0070          BTBL=M*1.48*((25./M)**1.0078)
0071          CAL=BTBL+16.
0072          CSW=17.68*M*(25./M)**.4436
0073          RWT=28.52*M*(25./M)**.4693
0074          GO TO 400
        C
        C     60 KVDC LESS THAN VOLTAGE LESS THAN 200 KVDC
        C     MVA GREATER THAN 20
        C     POLES = 4
        C
0075    145   SW1=C71.8*((25./M)**.345)
0076          X=.3345*((M   /25.)**.22472)
0077          SW2=SW1*((V/60.)**X)
0078          WG=M*SW2
0079          FLSL1=M*10.14096*((25./M)**.23256)
0080          FLSL2=M*8.9784*((M/25.)**.052227)
0081          FLSL=FLSL1-(200.-V)/140.*(FLSL1-FLSL2)
0082          LHM1=1.7822*M*((25./M)**.463468)
0083          LHM2=2.235*M*((25./M)*.962462)
0084          LHM=LHM1-(200.-V)/140.*(LHM1-LHM2)+.699*M+.20
0085          NLSL1=M*1.64676*((25./M)**.51224)
0086          NLSL2=M*1.9723*((25./M)**.95156)
0087          NLSL=NLSL1-(200.-V)/140.*(NLSL1-NLSL2)
0088          PRFT1=M*.0086142*((25./M)**.20433)+P
0089          PRFT2=M*.0070056*((M/25.)**.24274)+P
0090          PRFT=PRFT1-(200.-V)/140.*(PRFT1-PRFT2)
0091          VCLG1=.528*M*((25./M)**.08988)
0092          VCLG2=.34248*M*((25./M)**.11627)
0093          VCLG=VCLG1-(200.-V)/140.*(VCLG1-VCLG2)
0094          DCF1=1.2594*M*(25./M)**.54932
0095          DCF2=1.1499*M*(25./M)**.54276
0096          DCF=DCF1-(200.-V)/140.*(DCF1-DCF2)
0097          BTBL1=1.472*M*(25./M)**1.0076
0098          BTBL2=1.164*M*(25./M)**.9950
```

```
0099             BTBL=BTBL1-(200.-V)/140.*(BTBL1-BTBL2)
0100             CAL=BTBL+16.
0101             CSW1=16.32*M*(25./M)**.4460
0102             RWT1=26.55*M*(25./M)**.46815
0103             CSW2=12.72*M*(25./M)**.46426
0104             RWT2=21.95*M*(25./M)**.47065
0105             CSW=CSW1-(200.-V)/140.*(CSW1-CSW2)
0106             RWT=RWT1-(200.-V)/140.*(RWT1-RWT2)
0107             GO TO 400
           C
           C     60 KVDC LESS THAN VOLTAGE LESS THAN 200 KVDC
           C     MVA GREATER THAN 20
           C     POLES = 6
           C
0108       150   SW1=077.6*((25./M)**.4966)
0109             X=.3345*((M/25. )**.22473)
0110             SW2=SW1*((V/60.)**X)
0111             WG=M*SW2
0112             FLSL1=M*17.9201*((25./M)**.64195)
0113             FLSL2=M*12.6844*((25./M)**.034256)
0114             FLSL=FLSL1-(200.-V)/140.*(FLSL1-FLSL2)
0115             LHM1=3.0229*M*((25./M)**.721472)
0116             LHM2=3.4754*M*((25./M)**1.04052)
0117             LHM=LHM1-(200.-V)/140.*(LHM1-LHM2)+.699*M+.2
0118             NLSL1=2.70*M*((25./M)**.69934)
0119             NLSL2=3.146*M*((25./M)**1.04169)
0120             NLSL=NLSL1-(200.-V)/140.*(NLSL1-NLSL2)
0121             PRFT1=.0111688*((25./M)**.185385)*M+P
0122             PRFT2=.009538*((M/25.)**.15699)*M+P
0123             PRFT=PRFT1-(200.-V)/140.*(PRFT1-PRFT2)
0124             VOLG1=.5569*M*((25./M)**.17308)
0125             VOLG2=.37136*M*((25./M)**.03645)
0126             VOLG=VOLG1-(200.-V)/140.*(VOLG1-VOLG2)
0127             DCF1=1.124*M*(25./M)**.5684
0128             DCF2=1.016*M*(25./M)**.5666
0129             DCF=DCF1-(200.-V)/140.*(DCF1-DCF2)
0130             BTBL1=1.789*M*(25./M)**1.0162
0131             BTBL2=1.48 *M*(25./M)**1.0078
0132             BTBL=BTBL1-(200.-V)/140.*(BTBL1-BTBL2)
0133             CAL=BTBL+16.
0134             CSW1=23.28*M*(25./M)**.4314
0135             RWT1=33.12*M*(25./M)**.4570
0136             CSW2=17.68*M*(25./M)**.4436
0137             RWT2=22.52*M*(25./M)**.4693
0138             CSW=CSW1-(200.-V)/140.*(CSW1-CSW2)
0139             RWT=RWT1-(200.-V)/140.*(RWT1-RWT2)
0140       400   WGM=WG*.4536
0141             VOLGY=VOLG*.02832
0142             WGB=20.
0143             WGBM=WGB*.4536
0144             VGB=.3333
0145             VGBM=VGB*.02832
0146             WLP=5.2
0147             WLPM=WLP*.4536
0148             VLP=.02
0149             VLPM=VLP*.02832
0150             WLFL=15.3
0151             WLFLM=WLFL*.4536
```

```
      VLFL=.C88
      VLFLM=VLFL*.02832
      WLHF=12.
      WLHFM=WLHF*.4536
      VLHF=.208
      VLHFM=VLHF*.02832
      WHM=LHM*.298
      WHMM=WHM*.4536
      VHM=LHM*.00272
      VHMM=VHM*.02832
      GPM=FLSL*.4458
      WPMT=.13*GPM
      WPMTM=WPMT*.4536
      VPMT=.001736*GPM
      VPMTM=VPMT*.02832
      WTHF=.18*GPM
      WTHFM=WTHF*.4536
      VTHF=.0032*GPM
      VTHFM=VTHF*.02832
      WSHF=.749*NLSL
      WSHFM=WSHF*.4536
      VSHF=.0206*NLSL
      VSHFM=VSHF*.02832
      WEPS=27.+.52*M
      WEPSM=WEPS*.4536
      VEPS=.723+.00278*M
      VEPSM=VEPS*.02832
      FW=WG+WGB+WLP+WLFL+WLHF+WHM+WPMT+WTHF+WSHF+WEPS
      FWM=FW*.4536
      FV=VOLG+VGB+VLP+VLFL+VLHF+VHM+VPMT+VTHF+VSHF+VEPS
      FVM=FV*.02832
      VHFLM=.0015*M*((10./M)**.82125)*CCLD
      VHEL=.05297*M*((10./M)**.82125)*CCLD
      WHEL=.41265*M*((10./M)**.82125)*CCLD
      WHELM=WHEL*.4536
      WOD=.7005*M*((10./M)**.82125)*CCLD+35.
      WODM=WOD*.4536
      D1=(VHEL/.4/3.14159)**.33333
      D2=D1+.5
      VOD=.4*3.14159*(D2**3.)*1.2
      VODM=VOD*.02832
      WWFL=FLSL*ON*CYCLES*.0009624
      WWFLM=WWFL*.4536
      VWFL=WWFL/62.4
      VWFLM=VWFL*.02832
      WWNL=NLSL*XIDLE*60.*.75*.0009624
      WWNLM=WWNL*.4536
      VWNL=WWNL/62.4
      VWNLM=VWNL*.02832
      VW=VWNL+VWFL
      D3=(7.2*VW/3.1416)**.3333
      D4=D3+.017
      WWTP=5.+(D4**3.-D3**3.)*90.478
      WWTPM=WWTP*.4536
      VWTP=.5236*(D4**3.)+.1
      VWTPM=VWTP*.02832
      TW=FW+WHEL+WOD+WWFL+WWNL+WWTP
      TWM=TW*.4536
```

```
0210                TV=FV+VOD+VWTP
0211                TVM=TV*.02832
0212                DCFM=DOF*.0254
0213                BTBLM=BTBL*.0254
0214                CALM=CAL*.0254
0215                FCPM=LHM*.3577
0216                RFP=.207*(M/10.)**.1629*M
0217                AIRF=NLSL*.01234
0218                RPP=GPM*.033
0219                FREQ=47.13*(50./M)**.5*PL
0220                RPM=5656.*(50./M)**.5
0221                RCTD=17.*(M/50.)**.5+1.94
0222                RMI=RWT*(ROTD)**2./3091.2
0223                VHECD=CSW/1.797
0224                VHELN=VHECD*.25
0225                XHEP=3000.
           C
           C
           C        TABLE 1
           C
           C
0226       450      WRITE(3,451)WG,WGM,VCLG,VCLGM,WGB,WGBM,VGB,VGBM,WLP,WLPM,VLP,VLPM,
                   1WLFL,WLFLM,VLFL,VLFLM,WLHE,WLHEM,VLHE,VLHEM,WHM,WHMM,VHM,VHMM,
                   1WPMT,WPMTM,VPMT,VPMTM,WTHE,WTHEM,VTHE,VTHEM,WSHE,WSHEM,
                   1VSHE,VSHEM,WEPS,WEPSM,VEPS,VEPSM,
                   1FW,FWM,FV,FVM,WHEL,WHELM,VHEL,VHELM,WCD,WCDM,VCD,VCDM,WWFL,WWFLM,
                   1VWFL,VWFLM,WWNL,WWNLM,VWNL,VWNLM,WWTP,WWTPM,VWTP,VWTPM,TW,TWM,TV,
                   1TVM
0227       451      FORMAT('   COMPONENT          '7X'        WEIGHT    WEIGHT    VOLUME
                   1      VOLUME'/
                   14X'                                   LBS     KILOGRAMS  CU. FT.  CU.
                   1 METERS'//
                   1' GENERATOR                         '4F10.4  /
                   1' GEAR BOX                          '4F10.4  /
                   1' LUB PUMPS                         '4F10.4  /
                   1' LUB FITTINGS-VALVES-LINES         '4F10.4  /
                   1' LUB HEAT EXCHANGER                '4F10.4  /
                   1' HYDRAULIC MOTOR                   '4F10.4  /
                   1' T-OIL MOTOR-PUMP-TANK             '4F10.4  /
                   1' T-OIL FITTINGS-HOSE               '4F10.4  /
                   1' T-OIL HEAT EXCHANGER              '4F10.4  /
                   1' EXCITATION POWER EQUIPMENT        '4F10.4  /
                   1' TOTAL FIXED WEIGHT & VOLUME       '4F10.4  /
                   1' EXPENDABLES                       '        /
                   1'     LIQUID HELIUM                 '4F10.4 /
                   1'     DEWAR                         '4F10.4  /
                   1'     WATER,FULL LOAD               '4F10.4  /
                   1'     WATER,NO   LOAD               '4F10.4  /
                   1' WATER TANK AND PUMPS              '4F10.4  //
                   1' TOTAL                             '4F10.4  )
           C
           C
           C        TABLE 2
           C
           C
0228                WRITE(3,3)
0229                WRITE(3,1)
0230                WRITE(3,2)P,V,PF,PL,DN,CYCLES,XIDLE,COLD
```

```
0231            WRITE(3,452)
0232      452   FORMAT('          DIMENSIONS  OF  GENERATOR'////)
0233            WRITE(3,453)DOF,DOFM,BTBL,BTBLM,CAL,CALM
0234      453   FORMAT( ' DIAMETER OF FRAME        'F10.4,'INCHES   'F10.4,'METERS'//
               1        ' BEARING TO BEARING DIS 'F10.4,'INCHES   'F10.4,'METERS'//
               1        ' OVER ALL LENGTH         'F10.4,'INCHES   'F10.4,'METERS')
0235            WRITE(3,456)
0236      456   FORMAT(/////,8X' REQUIREMENTS ON AIRCRAFT SYSTEMS'/// )
0237            WRITE(3,454)XHEP,HGPM,REP,RPP,AIRF
0238      454   FORMAT(' HYDRAULIC FLUID'/'      PRESSURE 'F10.4,' PSI'/
               1                           '      FLOW     'F10.4,' GAL PER MIN'//
               1' EXCITATION POWER'/'    KVA          'F10.4,/
               1                     '   VOLTAGE      120/208, 3 PHASE'/
               1                     '   FREQUENCY    400 HERTZ'/
               1                     '   POWER FACTOR .90        '//
               1 ' POWER FOR PUMPS'/'   KVA          'F10.4,      /
               1                     '   VOLTAGE      120/280, 3 PHASE'/
               1                     '   FREQUENCY    400 HERTZ'/
               1                     '   POWER FACTOR .82        '//
               1 ' AIR FLOW     'F10.4,'LBS/SEC'/////
               1' AIR FLOW STATED AVOVE IS ADEQUATE FOR 25 PERCENT OF NO-LOAD,'/'
               1FULL EXCITATION LOSSES.  WATER CONSUMPTION FOR THIS MODE OF  '/'
               1OPERATION (IDLE) CAN BE DECREASED BY INCREASING THE      '/'
               1AIR FLOW RATE.     ')
          C
          C
          C     TABLE 3
          C
          C
0239            WRITE(3,3)
0240            WRITE(3,1)
0241            WRITE(3,2)P,V,PF,PL,ON,CYCLES,XIDLE,COLD
0242            WRITE(3,455)P,PL,FREQ,PRET,RWT,CSW,RPM,ROTD,RMI,FLSL,NLSL,VHECD,
               1VHELN,LHM
0243      455   FORMAT(9X   'MISCELLANEOUS DATA '/////
               1' POWER OUTPUT                     'F10.4,' MW'/
               1' POLES                            'F10.4,     /
               1' FREQUENCY                        'F10.4,' HERTZ'/
               1' POWER REQUIRED FROM TURBINE      'F10.4,' MW'/
               1' ROTOR WEIGHT                     'F10.4,' LBS'/
               1' COLD STRUCTURE WEIGHT            'F10.4,' LBS'/
               1'     ROTOR SPEED                  'F10.4,' RPM'/
               1'     ROTOR DIAMETER               'F10.4,' INCHES'/
               1' ROTOR MOMENT OF INERTIA          'F10.4,' LB-IN-SEC-SEC'/
               1' FULL LOAD STATOR LOSSES          'F10.4,' KW'/
               1' FULL EXCITATION NO LOAD          '/
               1' STATOR LOSSES                     'F10.4,' KW'/
               1' LIQUID HELIUM REQUIRED TO COOL'/
               1' ROTOR FROM ROOM TEMP.            'F10.4,' LITERS'/
               1' LIQUID HELIUM REQUIRED TO COOL'  /
         -     1' FROM LIQUID NITROGEN TEMP       'F10.4,' LITERS'/
               1' LOAD ON HYDRAULIC MOTOR         'F10.4,' KW ')
0244      500   CONTINUE
0245            CALL EXIT
0246            END
```

SUPERCONDUCTING GENERATOR, WESTINGHOUSE ELECTRIC CORP.

POWER MW	VOLTAGE KV	PF	POLES	ON TIME SEC	CYCLES	XIDLE MIN	COLD HOURS
25.0000	60.0000	1.0000	6.0000	120.0000	1.0000	10.0000	10.0000

COMPONENT	WEIGHT LBS	WEIGHT KILOGRAMS	VOLUME CU. FT.	VOLUME CU. METERS
GENERATOR	1939.9958	879.9836	9.2840	0.2629
GEAR BOX	20.0000	9.0720	0.3333	0.0094
LUB PUMPS	5.2000	2.3587	0.0200	0.0006
LUB FITTINGS-VALVES-LINES	16.8000	7.6205	0.0880	0.0025
LUB HEAT EXCHANGER	12.0000	5.4432	0.2080	0.0059
HYDRAULIC MOTOR	31.1589	14.1337	0.2844	0.0081
T-OIL MOTOR-PUMP-TANK	19.2023	8.7101	0.2564	0.0073
T-OIL FITTINGS-HOSE	26.5877	12.0602	0.4727	0.0134
T-OIL HEAT EXCHANGER	58.9088	26.7210	1.6202	0.0459
EXCITATION POWER EQUIPMENT	40.0000	18.1440	0.7925	0.0224
TOTAL FIXED WEIGHT & VOLUME	2169.8564	984.2468	13.3595	0.3783
EXPENDABLES				
LIQUID HELIUM	48.6086	22.0489	6.2397	0.1767
DEWAR	117.5163	53.3054	16.1887	0.4585
WATER,FULL LOAD	36.6224	16.6119	0.5869	0.0166
WATER,NO LOAD	34.0617	15.4504	0.5459	0.0155
WATER TANK AND PUMPS	13.8234	6.2703	1.5102	0.0428
TOTAL	2420.4880	1097.9331	31.0584	0.8796

SUPERCONDUCTING GENERATOR, WESTINGHOUSE ELECTRIC CORP.

POWER MW	VOLTAGE KV	PF	POLES	ON TIME SEC	CYCLES	XIDLE MIN	COLD HOURS
25.0000	60.0000	1.0000	6.0000	120.0000	1.0000	10.0000	10.0000

DIMENSIONS OF GENERATOR

DIAMETER OF FRAME	25.4000INCHES	0.6452METERS
BEARING TO BEARING DIS	37.0000INCHES	0.9398METERS
OVER ALL LENGTH	53.0000INCHES	1.3462METERS

REQUIREMENTS ON AIRCRAFT SYSTEMS

HYDRAULIC FLUID
PRESSURE 3000.0000 PSI
FLOW 100.1371 GAL PER MIN

EXCITATION POWER
KVA 6.0075
VOLTAGE 120/208, 3 PHASE
FREQUENCY 400 HERTZ
POWER FACTOR .90

POWER FOR PUMPS
KVA 4.8744
VOLTAGE 120/280, 3 PHASE
FREQUENCY 400 HERTZ
POWER FACTOR .82

AIR FLOW 0.9705LBS/SEC

AIR FLOW STATED AVOVE IS ADEQUATE FOR 25 PERCENT OF NO-LOAD, FULL EXCITATION LOSSES. WATER CONSUMPTION FOR THIS MODE OF OPERATION (IDLE) CAN BE DECREASED BY INCREASING THE AIR FLOW RATE.

SUPERCONDUCTING GENERATOR, WESTINGHOUSE ELECTRIC CORP.

POWER MW	VOLTAGE KV	PF	POLES	ON TIME SEC	CYCLES	XIDLE MIN	COLD HOURS
25.0000	60.0000	1.0000	6.0000	120.0000	1.0000	10.0000	10.0000

MISCELLANEOUS DATA

POWER OUTPUT	25.0000	MW
POLES	6.0000	
FREQUENCY	399.9109	HERTZ
POWER REQUIRED FROM TURBINE	25.2384	MW
ROTOR WEIGHT	712.9995	LBS
COLD STRUCTURE WEIGHT	441.9998	LBS
ROTOR SPEED	7998.7891	RPM
ROTOR DIAMETER	13.9608	INCHES
ROTOR MOMENT OF INERTIA	44.9556	LB-IN-SEC-SEC
FULL LOAD STATOR LOSSES	317.1099	KW
FULL EXCITATION NO LOAD STATOR LOSSES	78.6500	KW
LIQUID HELIUM REQUIRED TO COOL ROTOR FROM ROOM TEMP.	245.9654	LITERS
LIQUID HELIUM REQUIRED TO COOL FROM LIQUID NITROGEN TEMP	61.4913	LITERS
LOAD ON HYDRAULIC MOTOR	104.5600	KW

I. Graphical Illustration of Data

Results obtained from the algorithm computer code are graphically illustrated in Figures II-11 through II-18. Two specific weights for the subsystem are given for each design. The solid line represents the system weight with a steel dewar for the helium and the broken line represents the system weight with a light weight dewar constructed of aluminum and titanium.

SUPERCONDUCTING GENERATOR

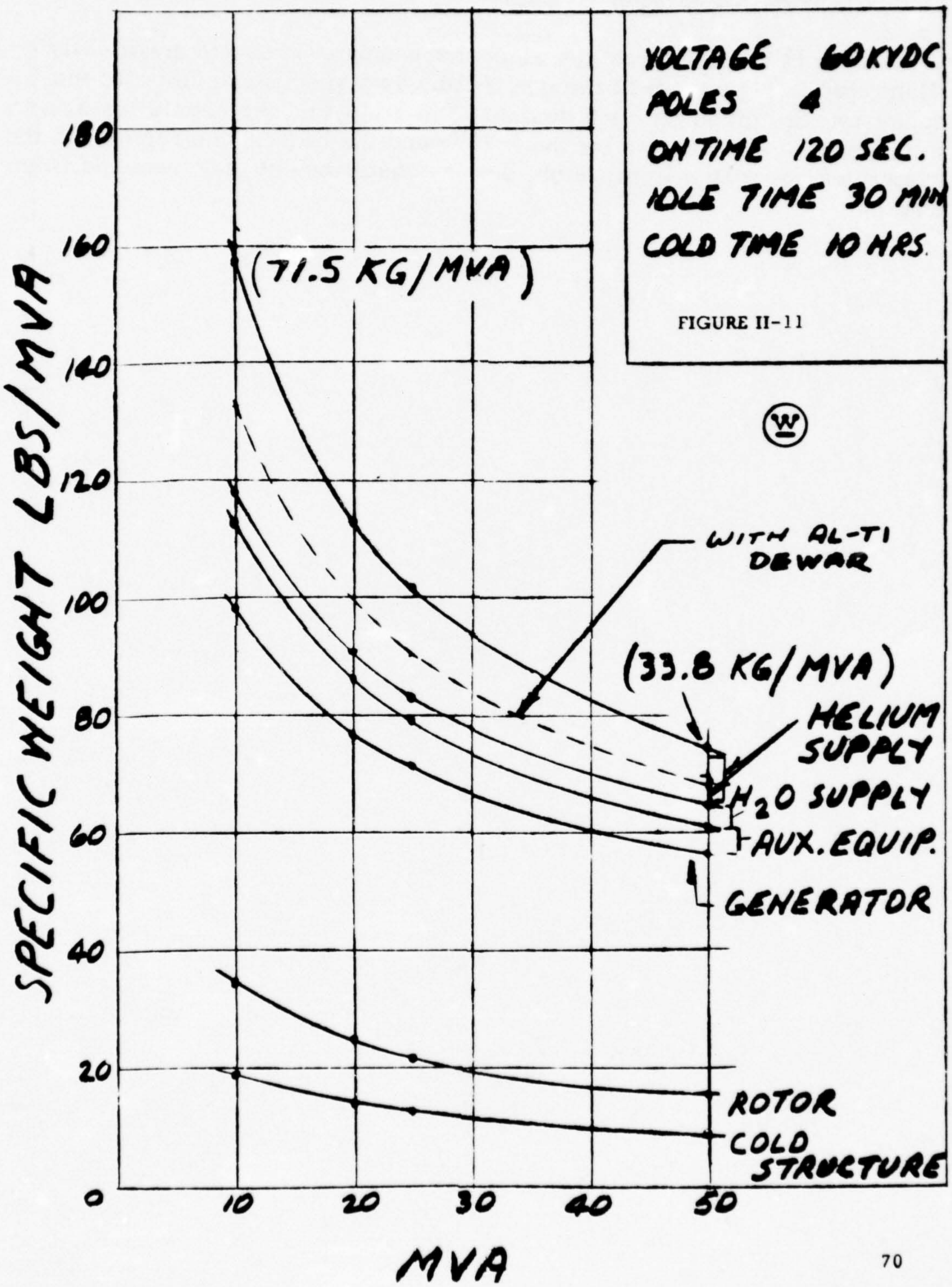


FIGURE II-11

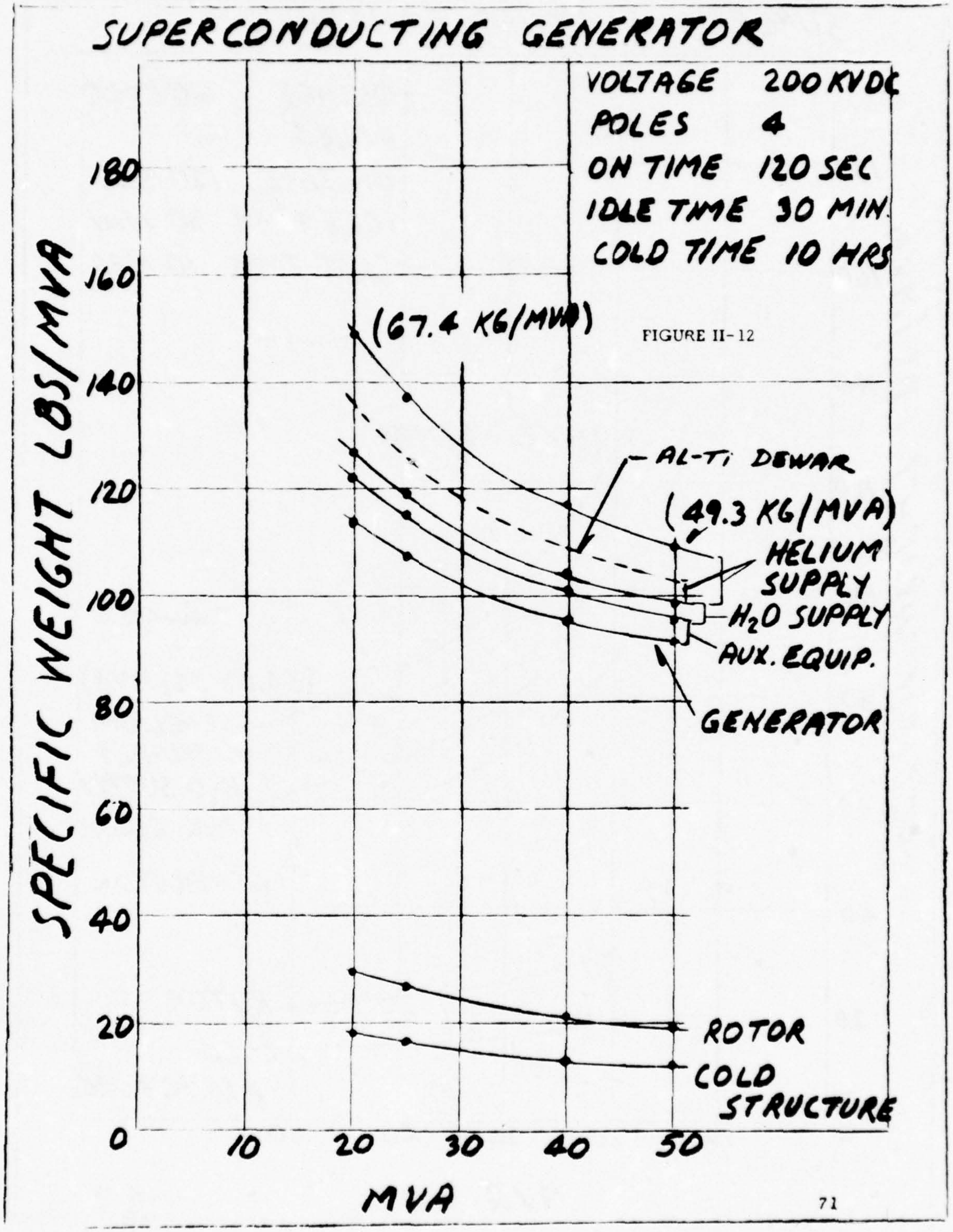

SUPERCONDUCTING GENERATOR
VOLTAGE 200 KVDC
POLES 4
ON TIME 120 SEC
IDLE TIME 30 MIN.
COLD TIME 10 HRS
(67.4 KG/MVA)
AL-TI DEWAR
(49.3 KG/MVA)
HELIUM SUPPLY
H_2O SUPPLY
AUX. EQUIP.
GENERATOR
ROTOR
COLD STRUCTURE
SPECIFIC WEIGHT LBS/MVA
MVA
0
10
20
30
40
50
60
80
100
120
140
160
180

FIGURE II-12

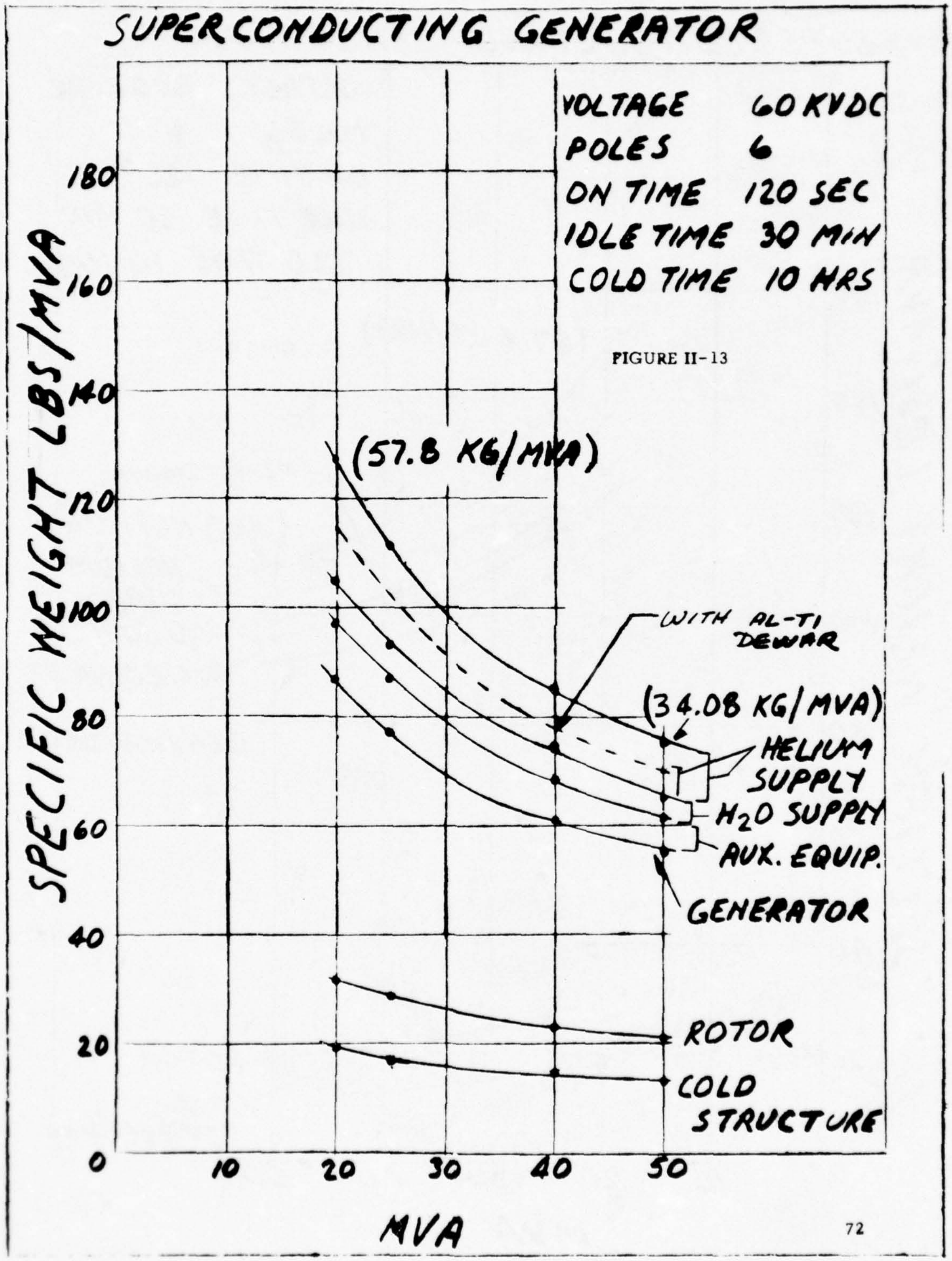

SUPERCONDUCTING GENERATOR
VOLTAGE 60 KVDC
POLES 6
ON TIME 120 SEC
IDLE TIME 30 MIN
COLD TIME 10 HRS
(57.8 KG/MVA)
WITH AL-TI DEWAR
(34.08 KG/MVA)
HELIUM SUPPLY
H_2O SUPPLY
AUX. EQUIP.
GENERATOR
ROTOR
COLD STRUCTURE
SPECIFIC WEIGHT LBS/MVA
0
20
40
60
80
100
120
140
160
180
10
20
30
40
50
MVA

FIGURE II-13

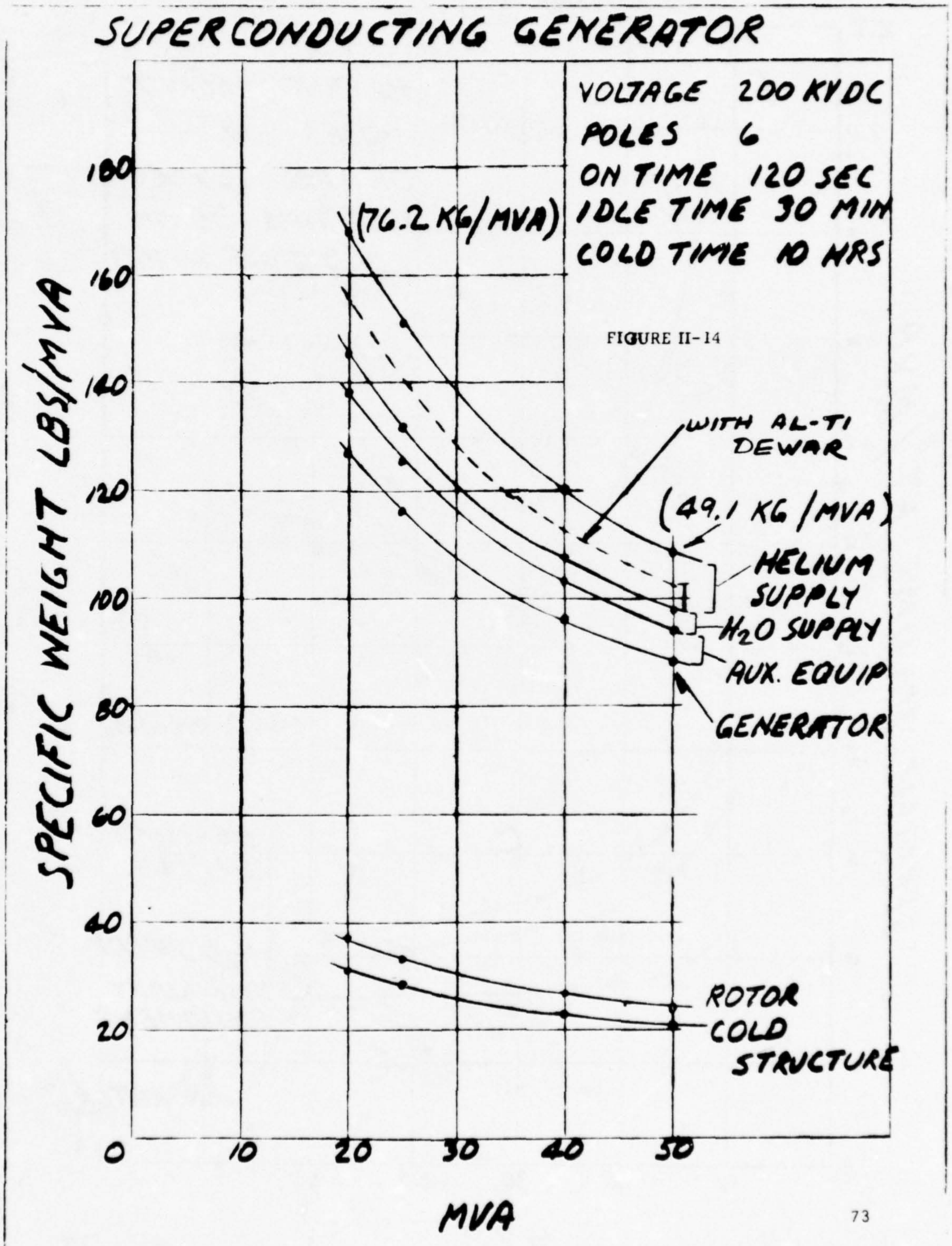
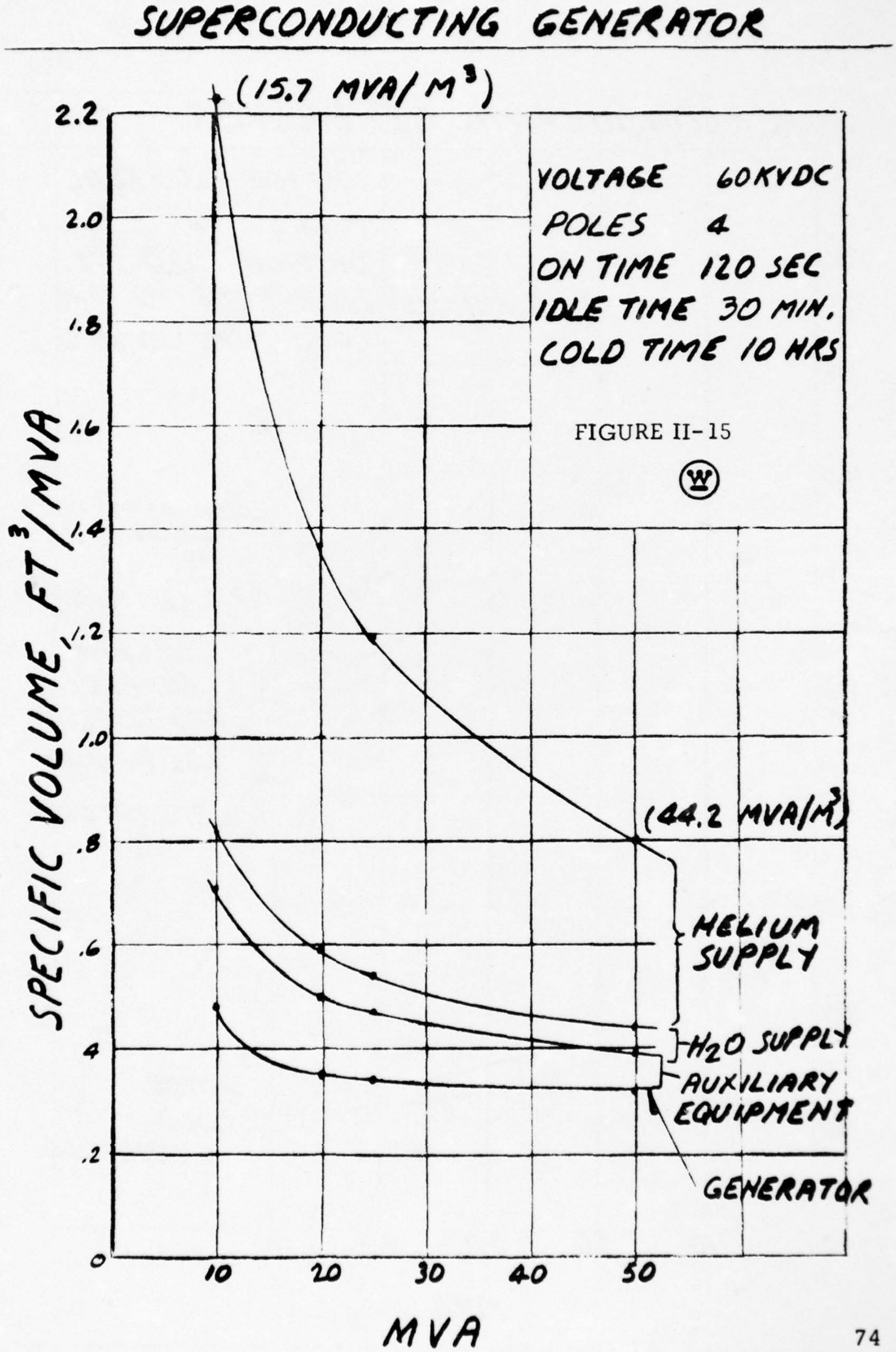

SUPERCONDUCTING GENERATOR
VOLTAGE 200 KVDC
POLES 6
ON TIME 120 SEC
IDLE TIME 30 MIN
COLD TIME 10 HRS
(76.2 KG/MVA)
WITH AL-TI DEWAR
(49.1 KG/MVA)
HELIUM SUPPLY
H_2O SUPPLY
AUX. EQUIP
GENERATOR
ROTOR
COLD STRUCTURE
SPECIFIC WEIGHT LBS/MVA
MVA
0
10
20
30
40
50
60
80
100
120
140
160
180

FIGURE II-14


SUPERCONDUCTING GENERATOR
(15.7 MVA/M³)
VOLTAGE 60KVDC
POLES 4
ON TIME 120 SEC
IDLE TIME 30 MIN.
COLD TIME 10 HRS
(44.2 MVA/M³)
HELIUM SUPPLY
H2O SUPPLY
AUXILIARY EQUIPMENT
GENERATOR
SPECIFIC VOLUME, FT³/MVA
MVA
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
4
.2
0
10
20
30
40
50
FIGURE II-15

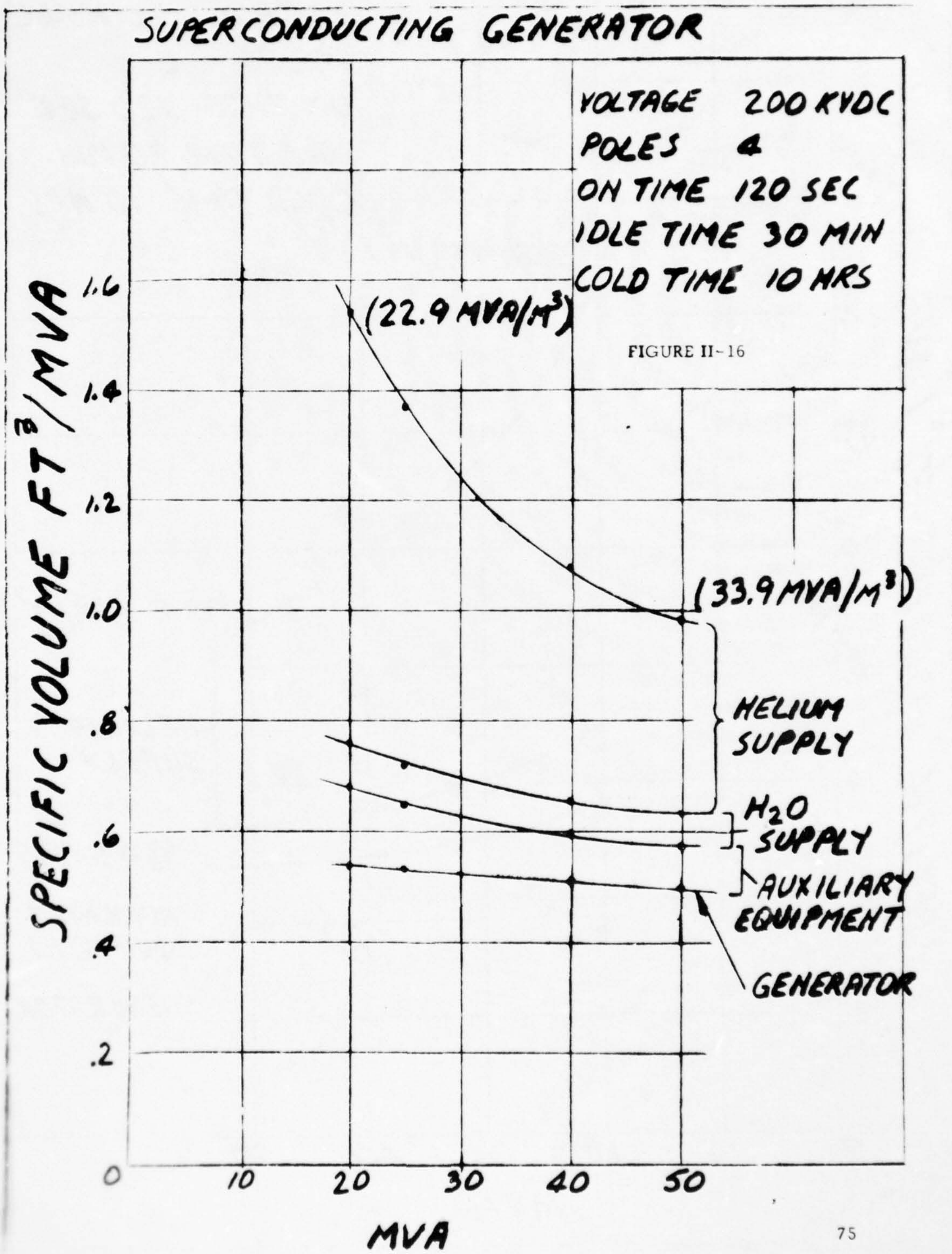

SUPERCONDUCTING GENERATOR
VOLTAGE 200 KVDC
POLES 4
ON TIME 120 SEC
IDLE TIME 30 MIN
COLD TIME 10 HRS
(22.9 MVA/M³)
(33.9 MVA/M³)
HELIUM SUPPLY
H2O SUPPLY
AUXILIARY EQUIPMENT
GENERATOR
SPECIFIC VOLUME FT³/MVA
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
10
20
30
40
50
MVA

FIGURE II-16

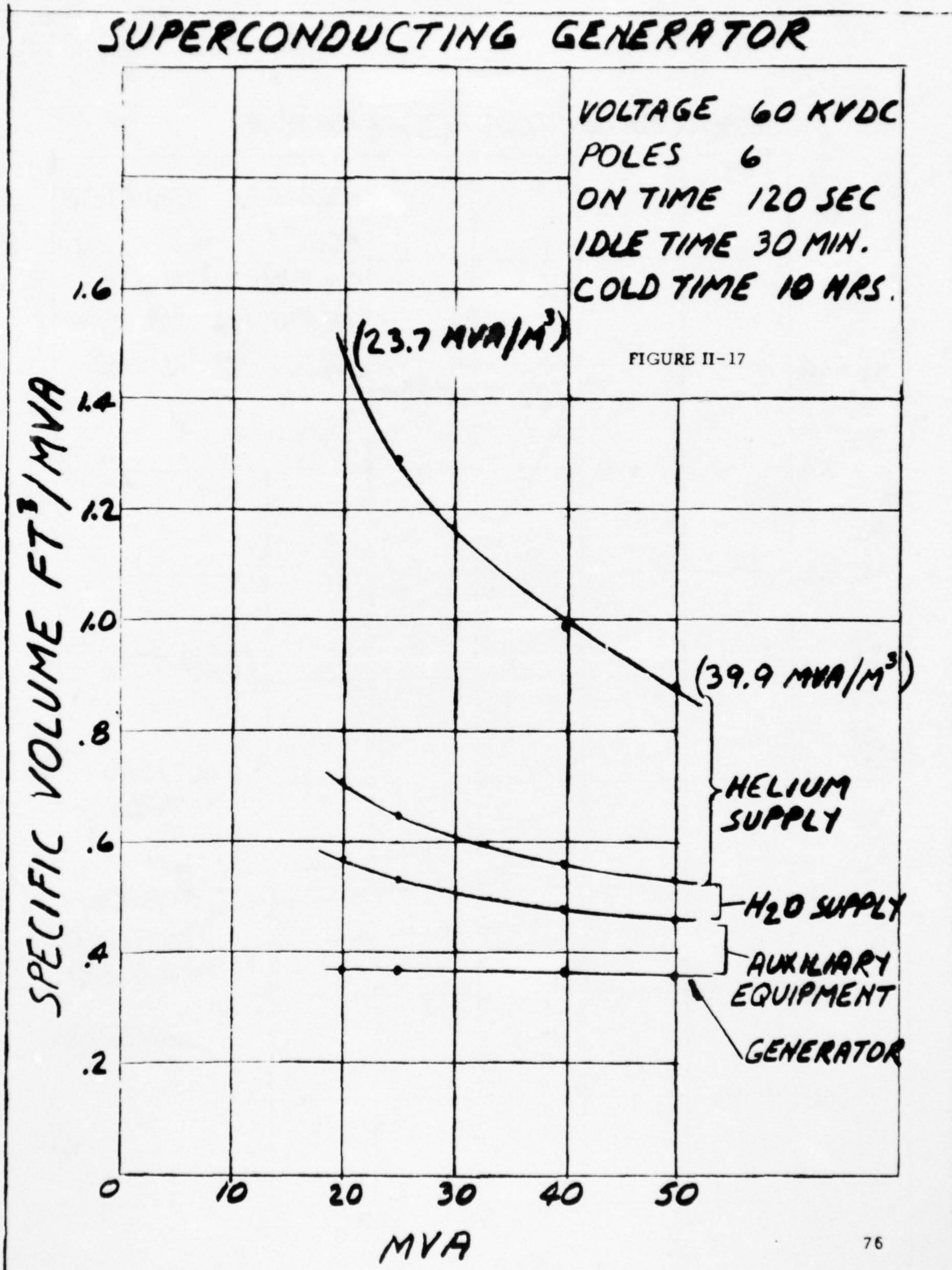

SUPERCONDUCTING GENERATOR
VOLTAGE 60 KVDC
POLES 6
ON TIME 120 SEC
IDLE TIME 30 MIN.
COLD TIME 10 HRS.
(23.7 MVA/M³)
(39.9 MVA/M³)
HELIUM SUPPLY
H₂O SUPPLY
AUXILIARY EQUIPMENT
GENERATOR
SPECIFIC VOLUME FT³/MVA
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
10
20
30
40
50
MVA

FIGURE II-17

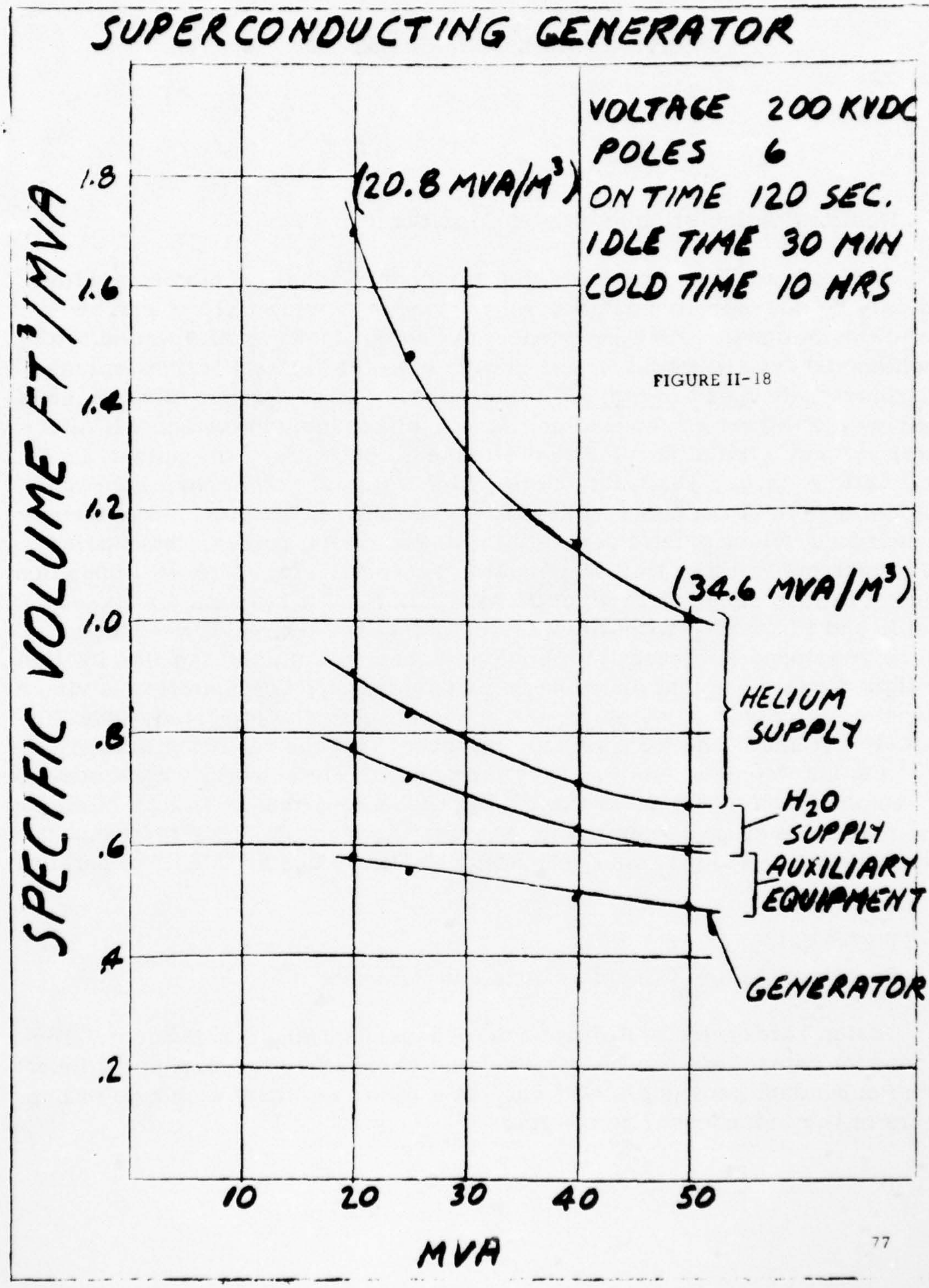

SUPERCONDUCTING GENERATOR
VOLTAGE 200 KVDC
POLES 6
ON TIME 120 SEC.
IDLE TIME 30 MIN
COLD TIME 10 HRS
(20.8 MVA/M³)
(34.6 MVA/M³)
HELIUM SUPPLY
H₂O SUPPLY
AUXILIARY EQUIPMENT
GENERATOR
SPECIFIC VOLUME FT³/MVA
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
10
20
30
40
50
MVA

FIGURE II-18

SECTION III

CONVENTIONAL GENERATORS

A. Design Configuration Selection Considerations

The work statement requires that the conventional generators studied need only be non-superconducting which leaves a wide field of choice open to the designer. Past experience has shown that the wire wound rotor (synchronous) type of machine will always give the lightest weight unless the turbine shaft speed is high. In that case, it is sometimes advantageous to employ a solid rotor type machine (e.g., either inductor or Lundell Alternators) to handle the high rotational stresses. Because of the unique load specifications (e.g., short duty cycle, high voltage), other more non-conventional generator concepts must also be considered, e.g., high frequency flux switches, electrostatic generators, linear motion pulsers, homopolar liquid brush generators, flux compression schemes, etc. A short discussion of some of these schemes is given in Appendix B. For reasons discussed therein, and in keeping with the philosophy that the technology proposed must be developed sufficiently to have an actual machine on the line by 1980, a straight forward, wound rotor synchronous generator configuration having a lap wound stator was selected for the conventional generator study (see Figure III-1). It should be emphasized, however, that the resulting designs are everything but "conventional". They represent the free-world's most advanced light weight, high power generator design technology that is in turn stretched to the limit of even projected advancements. As a result, they represent some relatively exotic designs when compared to a "truly conventional" generator.

B. Generator Design Considerations and Parameters

Design parameters are of two types: dependent and independent. The independent parameters can be adjusted and changed by the design engineer and the dependent parameters will vary as a direct result of a change of one or more of the independent parameters.

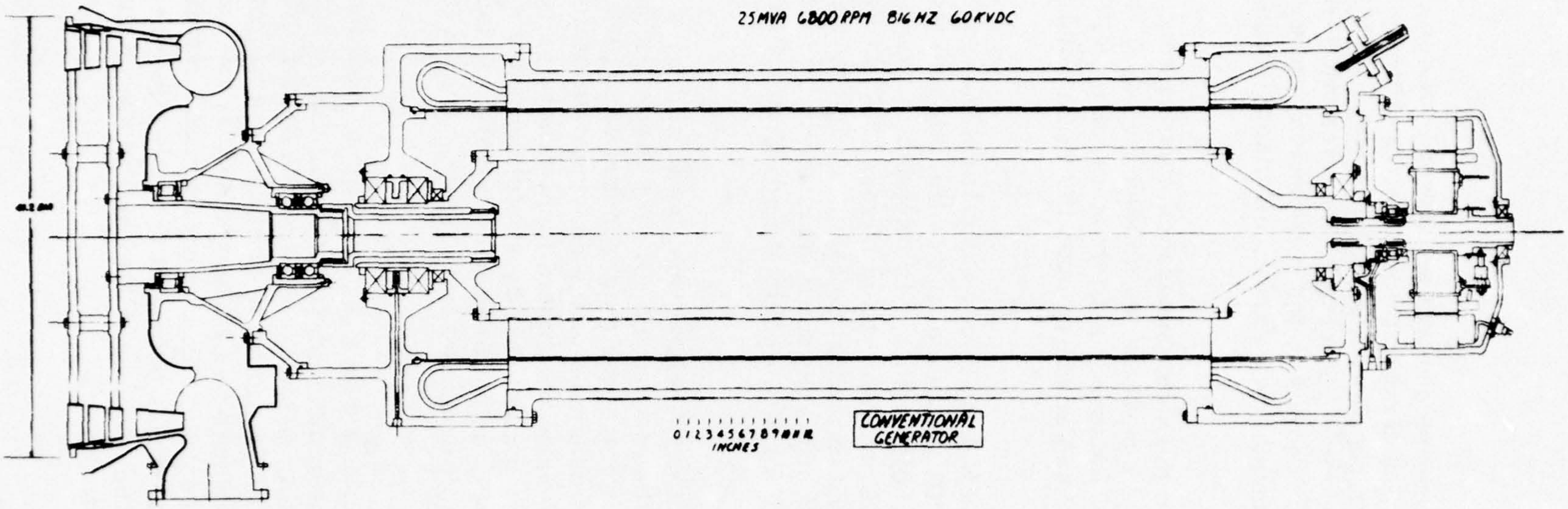

25MVA 6800RPM 816HZ 60KVDC
CONVENTIONAL GENERATOR
INCHES

FIGURE III-1

Examples of independent parameters are power, voltage, current density, rotor tip speed and machine configuration variables such as number of poles, conductors per slot, number of phases, rotor and stator diameters, number of slots, etc. The output characteristics will all be dependent parameters and a function of the independent parameters. Examples of these are: reactance, power factor, efficiency, regulation, weight and volume.

Power and voltage are the major independent parameters. Specifying the power and voltage of a machine determines the basic weight and size of the machine. Other independent parameters such as RPM and machine configuration will have an effect upon the weight and volume, but the effect is less.

In order to produce high dc voltage, a rectification system is necessary. An ac alternator will produce a line to line RMS voltage that is somewhat less than the dc voltage that it is intended to eventually result in. For example, a 60 KVDC machine would have a 48 KVAC line to line voltage and a 27.6 KVAC line to neutral voltage. As in the Superconducting Study of Section II, all of the output is assumed to be rectified to dc and the voltages discussed are given as dc; again, the rectifier to do this is not a part of the study.

The current density of the machine must be as high as practical without causing excessive heating problems. The current densities selected for the conventional rotors were in the neighborhood of 15,000 amps per square inch and the current densities of the conventional stators were in the neighborhood of 17,000 amps per square inch. These current density levels represent the highest conceivable by stretching today's technology. Higher stator current densities might have been possible had the stack lengths turned out to be short compared to the end extension lengths, but they did not.

One of the major problems with the conventional machine is cooling the conductors in order that a higher current density can be maintained. The overall weight is strongly related to the current density in that the higher the current density is, the lower is both the wire weight and steel weight. In addition, copper wire has little mechanical strength and depends upon the magnetic steel to hold it in position and contain it. Since the greatest amount of rotor stress occurs at the pole tips where the wire coil weight is supported, the maximum allowable tip speed also becomes a function of the current density.

Insulation thickness is dependent upon the voltage in a manner comparable to the Superconducting generator except one must now have a steel stack surrounding the coils. As a result, the insulation thickness increases rapidly with output voltage, see Figure III-2. For example, a conductor inside a slot on a 60 KVDC machine needs a minimum of 0.19 inches of insulation surrounding it, and the volume of iron needed to encompass that large slot becomes exponentially large.

The entire stator cavity must be flooded with transformer oil and vacuum filled to insure that all voids are filled with oil and not air. A basic law of electrostatics states that the total voltage across insulations in series is divided in proportions to the thickness of the individual insulations and inversely to the respective dielectric constants (K). A result of this relation is the concentration of voltage across the low dielectric constant media (such as air) whenever it appears in series with high dielectric constant solid material. The dielectric strength of air is about 50 volts per mil compared to a typical value of 300 volts per mil for transformer oil. The benefit of having transformer oil in the stator rather than air is that not only will the voltage stress concentration be less in oil ($K = 2.1$) than in air ($K = 1$), but the oil is also capable of withstanding six times the voltage stress that air is capable of withstanding. When generated voltages are as high as required in this application, attention must be given to the dielectric constant of the solid insulation selected to avoid overstressing the oil. A dielectric constant of 3.75 was used for the solid insulation in the study. Fiberglass-epoxy and other glass insulations have a dielectric constant of 4.0 to 4.5. The attainment of a constant of 3.75 or less will require the use of Kevlar or quartz fibers in epoxy-fiber systems.

Solid insulation must also be free of voids to obtain and maintain the required electrical strength. For epoxy-fiber systems, epoxy resin which has been formulated for the application must be applied by vacuum impregnation. Epoxy-fiber insulations would be used where mechanical strength is a strong consideration such as for the bore seal and supports. In the slot, however, high mechanical strength is not required and other insulation materials can be considered. Nomex insulation, a high temperature paper, has excellent electrical properties for use in oil filled, high voltage applications. Its dielectric constant is low, $K = 2.6$ to 3.5, and is somewhat porous so it can be impregnated with transformer oil. This impregnation with oil would keep the dielectric constant near or below the

WESTINGHOUSE ELECTRIC CORPORATION

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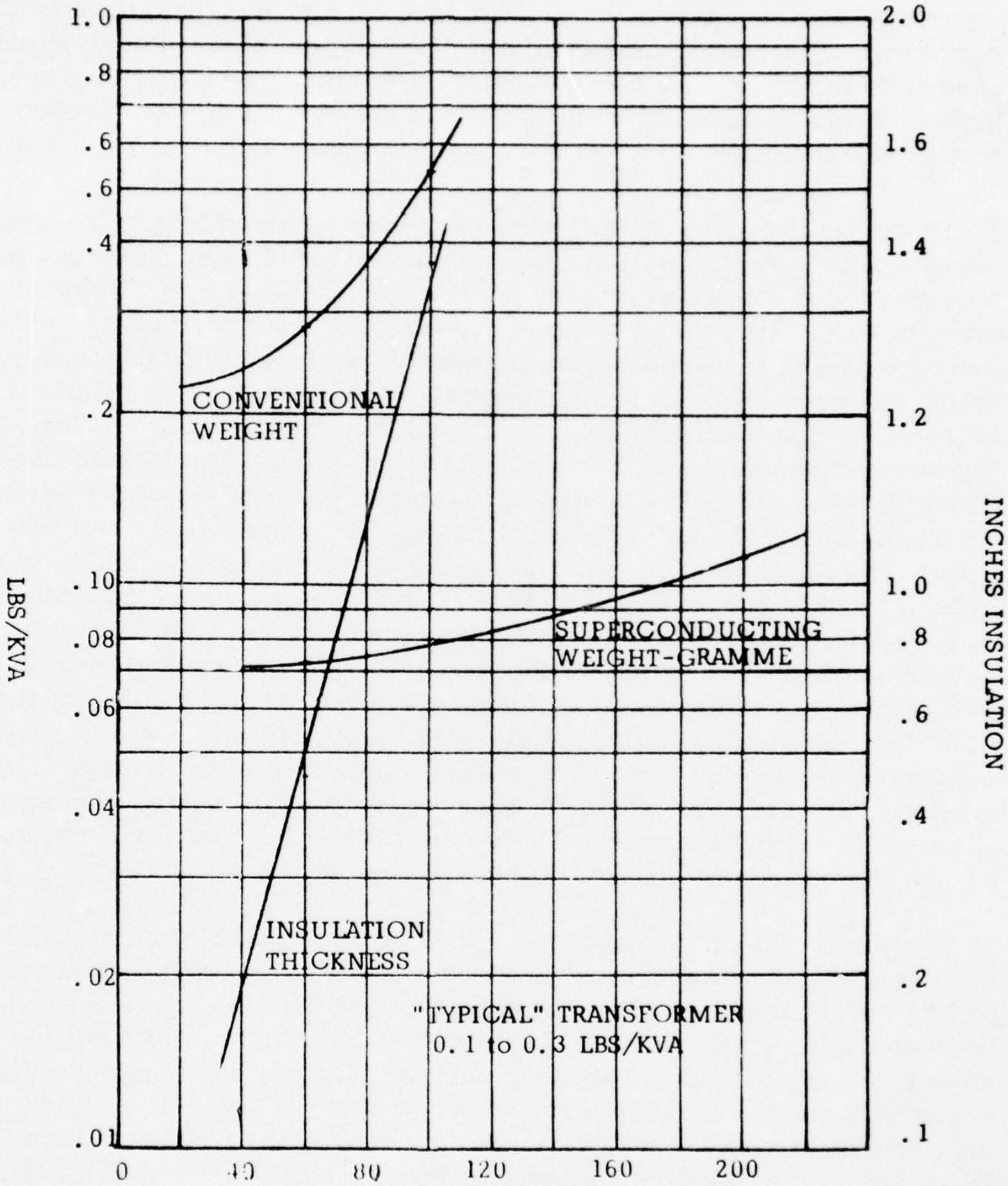
SPECIFIC WEIGHT & INSULATION THICKNESS VERSUS VOLTAGE



25 MVA

120 SECONDS ON TIME

Figure III-2

low value specified above and would therefore provide excellent voltage division between the solid insulation and oil filled areas. Dielectric strength of Nomex is approximately 700 volts per mil. The insulation thicknesses selected for the specified voltage levels were based on a dielectric constant of 3.75 and these values applied to Nomex slot insulation represent an achievable, conservative design.

An important consideration in the design of high voltage systems for airborne applications is the method of connecting the high voltage power source to the load. The most convenient method of connecting a source to its load is the use of electrical bushings (terminals) to which the feeder cables are simply attached. This method is not practical for voltages greater than a few thousand volts ac for most airborne applications. At higher voltages, alternate methods are necessary. As an example, the spacing required between electrical bushings for a 50 KVDC termination at an altitude of 40,000 feet is $4\frac{1}{2}$ feet based on flashover considerations only; corona minimization would require even more spacing.

With the optimum values of current density, insulation thickness, rotor tip speed and with the selection of the best machine configuration (conductors per slot, number of slots, number of poles, etc.) the weight and volume of the machine will be minimum for output power and voltages chosen and to a lesser degree for the shaft speed chosen. The latter will only affect the weight and volume by making the machine either short and fat or long and skinny.

A summary of the key design parameters used on all of the generator designs considered is given in Table III-1. The rotor tip speed was held to 700 ft/sec, and the length of the rotor was kept in proportion to the rotor diameter in order to insure rotor dynamic stability. The aspect ratio (rotor active length/rotor diameter) was kept below 3.5 to 1. The rotor dynamic stability really depends on the ratio or bearing-to-bearing length divided by rotor diameter. However, selection of the main rotor field aspect ratio is an important first step in establishing the bearing-to-bearing length/rotor diameter ratio.

To cover the range of power and voltage specified in Table I-1, nine base designs for conventional generators were made. Machines were designed at each of three power levels: 10 MVA, 25 MVA, and 50 MVA and at the voltage levels of 20 KVDC, 60 KVDC and 100 KVDC. With the data obtained from these base designs, three dimensional data surfaces were generated which give any dependent parameter such as weight or volume as a function of power and voltage. The curves were then modeled into an algorithm which was used as the computer code for the conventional generators. Over 2000 computer designs were actually used to achieve the optimum machine configuration for the nine base designs.

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

TABLE III-1

DESIGN PARAMETERS

RPM	6,000 - 10,000 RPM
ROTOR PERIPHERAL VELOCITY	700 FT/SEC
STATOR O. D.	19.7 - 32.7 INCHES
ROTOR O. D.	16.3 - 27.0 INCHES
ROTOR ASPECT RATIO	2.8 - 3.5 LENGTH/ROTOR O. D.
NUMBER OF POLES	12 - 16
FREQUENCY	700 - 1050 HERTZ
STATOR CURRENT DENSITY	17,000 AMPS/IN^2
ROTOR CURRENT DENSITY	15,000 AMPS/IN^2
FIELD CURRENT	200 AMPS
MAXIMUM FLUX DENSITY	100 KILOLINES/IN^2
FULL LOAD POWER FACTOR	$\geq$ .95
STATOR COOLANT	TRANSFORMER OIL
ROTOR COOLANT	LUBRICATING OIL

C. Configuration Highlights

1. Stator

The key components within the stator consist of 0.01 inch thick Fe Cobalt alloy punchings, ML enamel copper windings, high voltage insulation and a bore seal. A typical slot from a 60 KVDC, 25 MVA machine is shown in Figure III-3. The insulation fills a high percentage of this slot, and as the voltage of the machine goes up, percentage fill increases. In addition, a machine with a higher voltage output would require more conductors per slot. The different phases within the slot are separated by an insulation of sufficient thickness to insulate for line to line voltage. Between the conductors within one phase is an oil passage for cooling purposes.

Insulation from the conductors to the rotor is achieved by two pieces, the slot (top) wedge and a 0.1 inch thick bore seal. The bore seal encloses the stator inside diameter, isolating the transformer oil-coolant from the air gap and rotor.

The generator design programs used at Westinghouse allow for a calculated amount of end turn length in order to assure sufficient conductor spacing in the end turns. Even though more than sufficient room was left for the end turns (as called for by the design program), before any high voltage stators required for this application can be built, much effort will be required to develop the end turn configuration of the high voltage windings. This is because the proven design techniques used were only intended for lower voltage generators, and the spacing criteria therein may not be directly scaled.

2. Rotor

The power density of a large electric generator is increased by utilizing a rotor which has a high tip speed. The machines evaluated in this study ran at tip speeds of 700 ft/sec. Even though this is above any known speed for wound rotor machines used for light weight aircraft power generation, it is not unreasonable from the standpoint of stress. Above 700 ft/sec, the forces on the wire, insulation, pole head, and wedge become more limiting and the ability of the design to operate reliably becomes questionable.

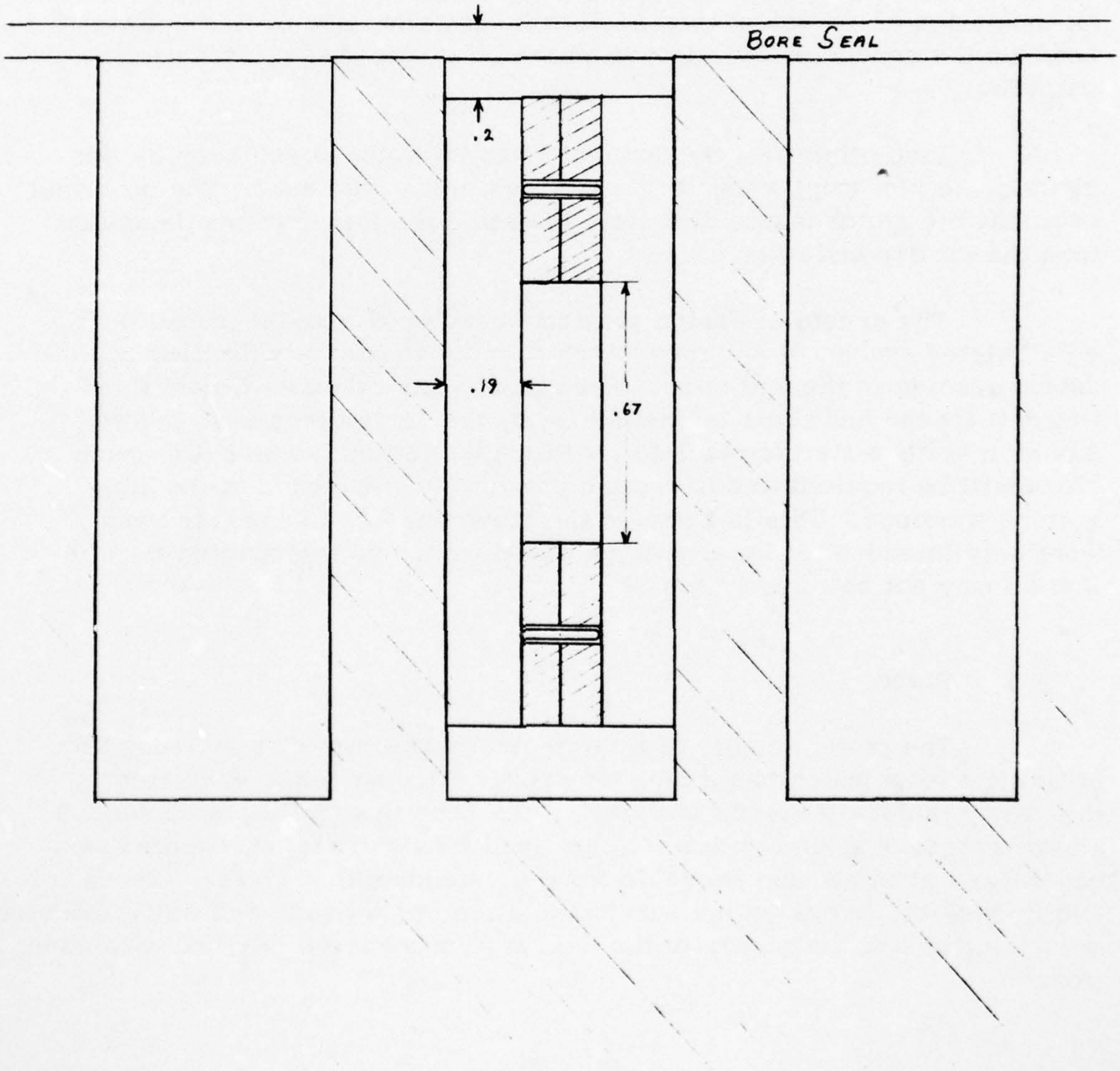
FIGURE III-3

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

SLOT DETAIL

25 MVA, 60 KVDC



High current densities make it possible to use less wire in the rotor coils and thus reduce the radial loading. However, this is countered by the weight of the necessary oil cooling ducts. A single wedge design for such a configuration would stress materials to their very limits. An alternative to the single wedge design is the use of two or more wedges to constrain the coils. Such a configuration is shown in Figure III-4. This approach divides the load on the coils, pole head, wedges and insulation and the operating stresses are thereby kept to a reasonable value.

3. Other Mechanical Parts (Reference Figure III-1)

The main machine consists primarily of five subassemblies - rotor, main ac stator, exciter generator, drive end bell and anti drive end bell.

The rotor consists primarily of the laminated stack, field coils, cooling ducts, main shaft, drive end stub shaft, anti-drive end stub shaft, and input drive spindle.

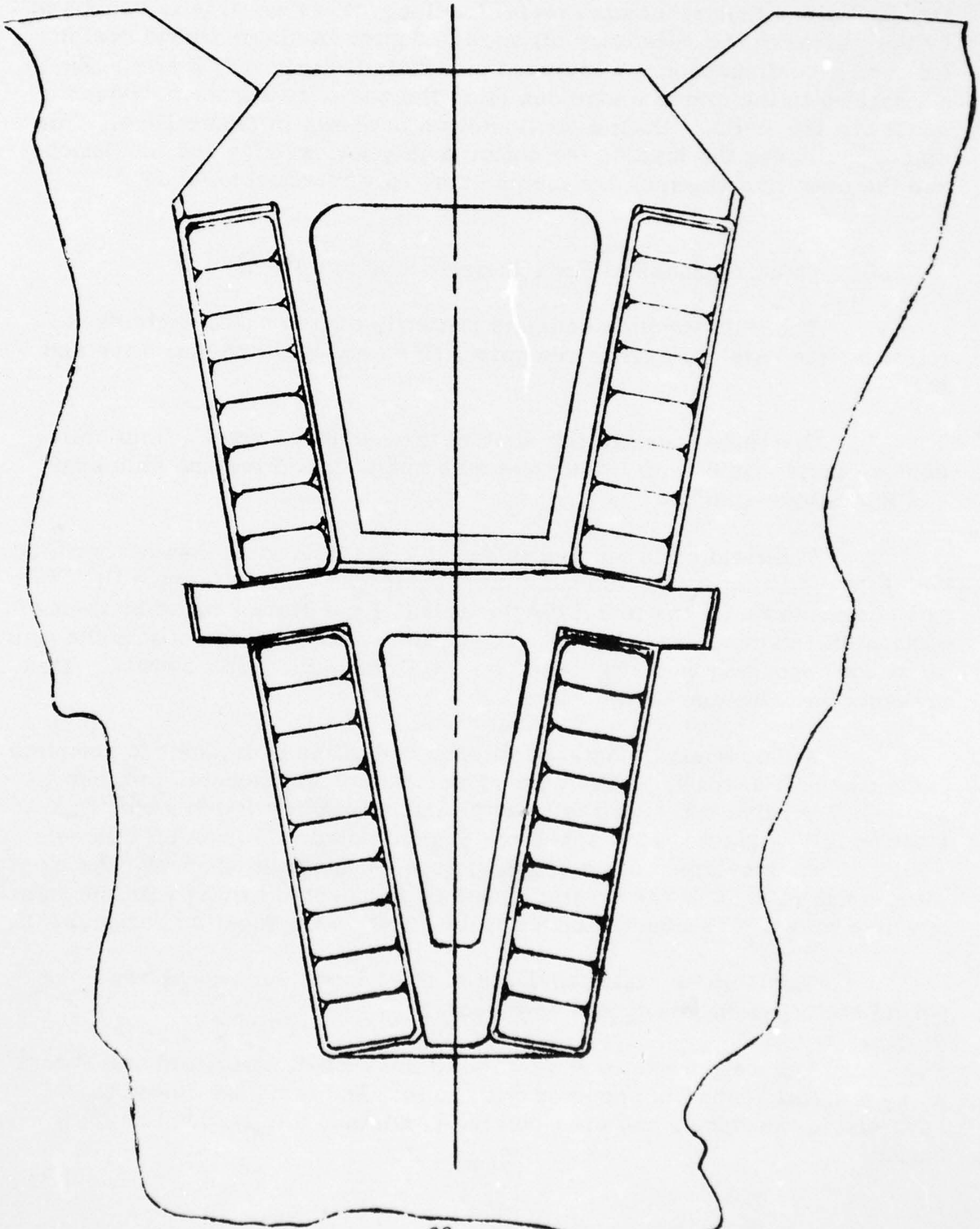
The field coils are assembled to the single piece laminated stack which is then shrunk onto the main rotor shaft with an interference fit. This is to compensate for the radial displacement of the stack caused by thermal expansion and centrifugal forces. In addition, a keyway is cut into the main shaft corresponding to a key formed on the ID of the laminated stack. This prevents any slippage on the shaft.

A stub shaft is fastened to each end of the main shaft to complete the main shaft assembly. The rotor shaft bearings are mounted to these shafts. The drive end stub shaft has an internal spline which mates to a floating drive spindle. The anti-drive end stub shaft also has an internal spline. This provides a drive coupling between the main shaft and the exciter armature shaft. The exciter generator is mounted in line with the main machine rotor but is mounted on a separate shaft with separate bearings.

The main ac stator consists of three basic subassemblies - the wound stator, main frame, and bore seal.

The main frame is assembled to the wound, laminated stator core using a shrink fit and is anchored with bolts. End bells are bolted to each end of the frame, and the mounting provisions are provided on their surface.

FIGURE III-4 TWO-WEDGE POLE CONSTRUCTION



AD-A031 620 WESTINGHOUSE ELECTRIC CORP LIMA OHIO AEROSPACE ELECT--ETC F/G 10/2
HIGH POWER STUDY SUPERCONDUCTING GENERATORS.(U)
MAR 76 A E KING, C C KOUBA, J L MCCABRIA F33615-75-C-2068
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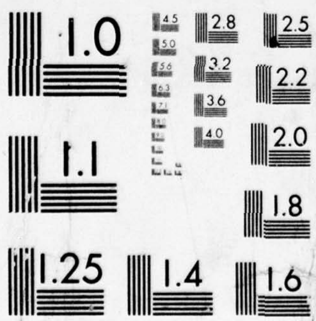


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Since the high ac stator voltages make it necessary to submerge the stator coils in oil, the stator core is sealed on the ID by a bore seal. This consists of an epoxy/glass laminated tube over which the stator is shrunk. In addition, the bore seal tube is bonded to the stator teeth. The bore seal mates with the end bells at each end and is sealed against leakage by use of O-rings.

D. Cooling System

For a machine to operate without overheating, the rate of heat removal must be equal to or greater than the rate at which it is generated. For continuous operation, a balanced or steady state condition must be reached at a temperature that will not destroy the generator components. The conventional machines studied herein are pulse loaded. Hence, it is not necessary that all of the heat be removed as it is generated. The primary concern is that the heat be removed at a rate sufficient to prevent damage or destruction of the generator components, in particular the (organic) insulations.

The simplest method of operating a pulse loaded system such as this might be to let the machine mass soak up all of the heat as it is generated. There are drawbacks to such an approach however. First, the rotor coils carry low voltage current. This permits the use of relatively thin insulating materials which does allow heat transfer from the coils to the steel in the rotor poles. However, with the rotor field coils excited between pulses, heat is being continuously generated during the full period of operation. These losses simply cannot be absorbed in the copper and steel alone without exceeding the limiting operating temperature of the rotor field coils (about 300°C; above this, the life of the enamel wire insulation drops rapidly).

Secondly, the ac stator operates at very high voltages so the conductors must be insulated with fairly thick materials specifically selected for their insulation-only properties. This places a very effective barrier to heat transfer from the copper conductors to the stator steel. In addition, to maintain the high voltage levels, the conductors must be submerged in transformer oil. This oil provides the necessary dielectric strength, but has a flash point of only about 275°F and the stator conductors must therefore be maintained at a relatively low operating temperature. In order to make the thermal-inertia

(or soak) method of cooling feasible, the conductor size would have to be increased to the point where the conductors alone could absorb the heat generated. When the conductor size is increased, the quantity of steel surrounding it also increases.

An alternate cooling method involves the use of a fluid to absorb the excess heat and transport it away from the point of origin. Since the stator is already submerged in oil, few additional changes are necessary to use oil as the cooling medium. Comparison of purely thermal inertia machines and a fluid cooled system tended to favor the latter. From the weight standpoint alone, the thermal inertia machines did not appear favorable except for run times of less than one-third minute (approximate). Fluid cooling provides more versatility in run times plus increasing weight savings as the operating time increases.

Figure III-5 shows a sectional view of a typical stator slot. To provide a flow path for the oil through the stack, spacers were added to separate wires of the same phase. This configuration allows the oil to come into direct contact with the conductors and effectively cool them. The transformer coolant oil flows the length of the stack and exits the generator to a heat exchanger.

Figure III-6 shows the oil flow path through the main generator rotor. The rotor coolant is MIL-L-7808 oil. The oil enters the anti-drive end of the generator through the hollow shaft, flows through the shaft to the anti-drive end stub shaft and exits radially through circular manifold tubes to cooling ducts in the rotor. The oil flows the entire length of the rotor stack picking up heat from the field coils. At the drive end, the oil flows inward through another set of circular manifold tubes into the drive end stub shaft assembly. The oil is forced to flow to the ID of a baffle, thereby giving up a portion of its head. This is to insure that a sufficient back pressure is created to balance the head produced by the radial holes in the anti-drive end stub shaft. The oil then spills out into a cavity formed between the first baffle and a second outer baffle. The second baffle chokes the oil flow to provide a smooth flow transition from the ID of the first baffle to the ID of the main shaft. The oil flows along the ID of the main shaft back to the anti-drive end of the generator where it is discharged through axial holes in the anti-drive end stub shaft to a cavity formed between the anti-drive end end bell and the wall support for the rotating seal. In addition to cooling the rotor, the oil is also used to lubricate the bearings.

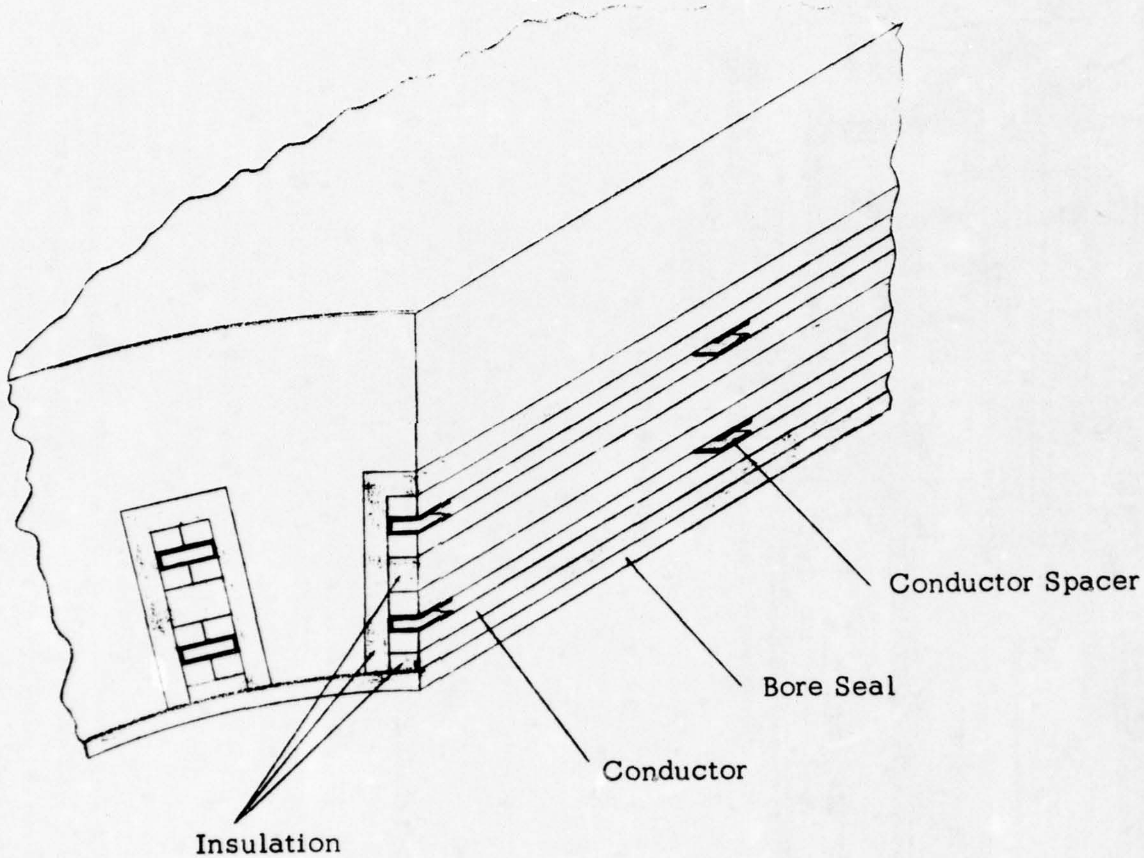
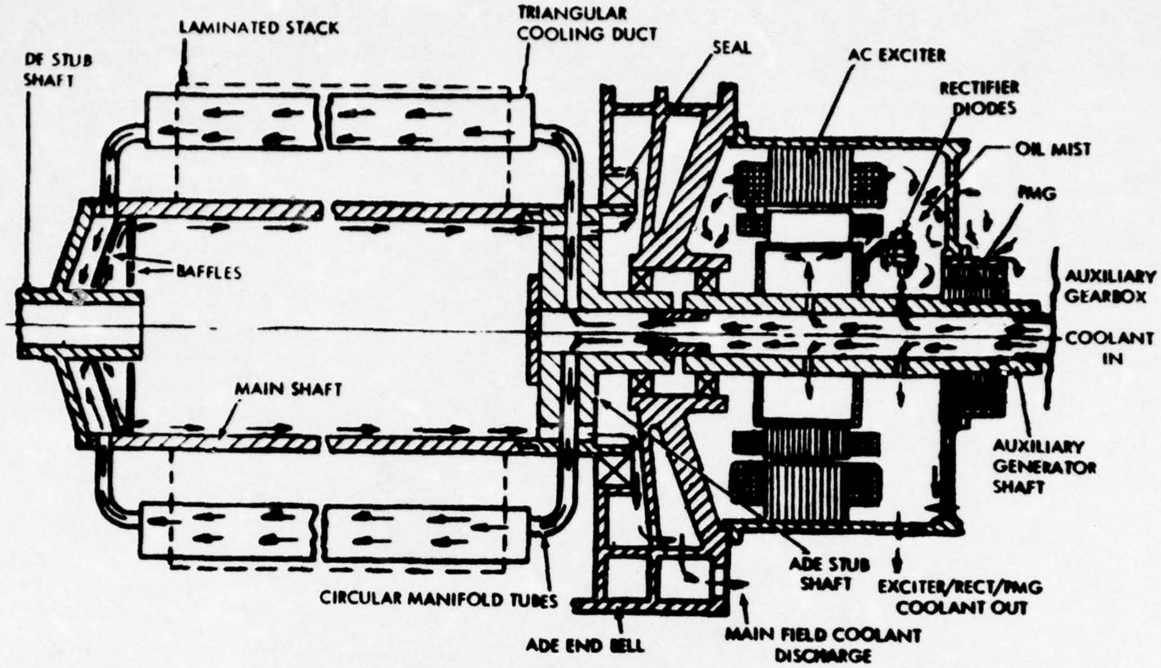


FIGURE III-5



Rotor Coolant Circuit

FIGURE III-6

DE - Drive End

ADE - Anti-Drive End

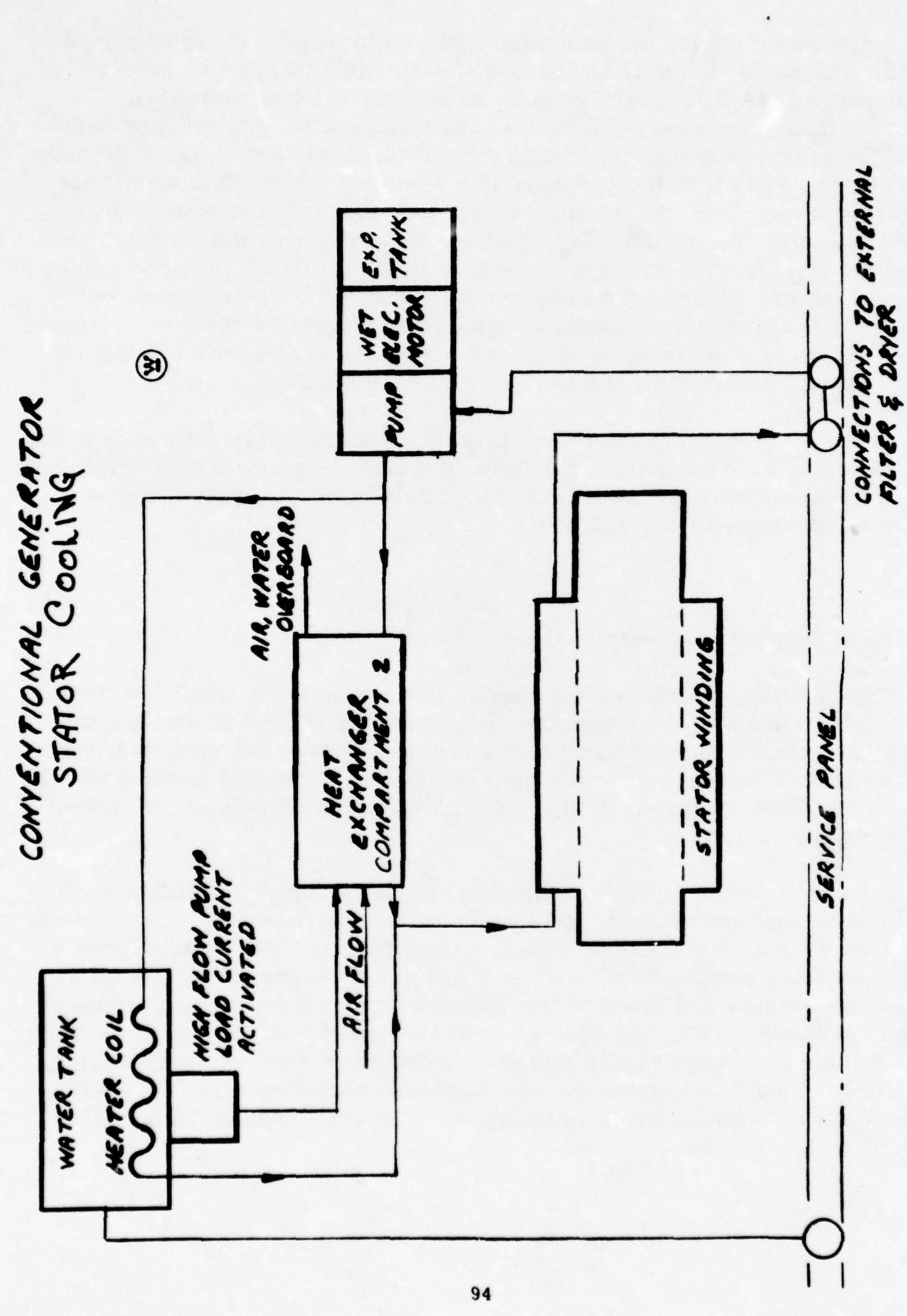
On most missions, the generator operates for relatively short periods of time. The mass of iron in the rotor and stator is sufficient to eventually absorb many of the iron losses without an appreciable temperature rise. The main concern is removing heat from the conductors. The oil flow paths within the generator insure the efficient removal of this heat. Once through the generator, the oil is pumped through a heat exchanger. The exchanger is sized to remove only the continuous no load, full voltage excitation losses. Oil passing through the exchanger under these operating conditions is cooled by air flowing over the exchanger surface. Under full load operations, air cooling alone is not sufficient. At full load conditions, the generator oil exit temperature increases until a preset level is reached to trigger a water injection pump to spray water onto the heat exchanger surfaces. The surplus heat is absorbed by the heat of vaporization of the water.

Since the rotor and stator use different coolants, separate pumps are required for each. In addition, the heat exchanger is built with two chambers to keep the coolants separated. Schematic diagrams of these systems are illustrated on Figures III-7 and III-8.

E. Point Designs, Conventional Generators

This section summarizes the results of the designs derived from the study. They are all of the same basic configuration (Figure III-1), but the internal parameters such as number of poles, conductors per slot, etc. were selectively determined to optimize the design for the required power and voltage levels. Cooling system data is also given which applies to the specific duty cycles of Table I-1.

Figures III-9 through III-12 illustrate weight, volume, optimum shaft speed (for stress) and rotor inertia as a function of MVA output over the range of 20 to 60 KVDC. Both generator weight (volume) and total system (generator plus coolers, pumps, etc.) weight (volume) are given. Table III-2 summarizes the weights and gives weight breakdowns for the various designs of Figures III-9 and III-10. Voltage and reactance parameters are given in Table III-3. Tables III-4 through III-7 summarize the point designs data; weight, dimensions, conductor parameters and excitation requirements. Losses, cooling data and cooling system parameters are summarized in Tables III-8 through III-12.



CONVENTIONAL GENERATOR
STATOR COOLING
WATER TANK
HEATER COIL
HIGH FLOW PUMP
LOAD CURRENT
ACTIVATED
AIR FLOW
HEAT
EXCHANGER
COMPARTMENT 2
AIR, WATER
OVERBOARD
PUMP
WET
ELEC.
MOTOR
EXP.
TANK
STATOR WINDING
SERVICE PANEL
CONNECTIONS TO EXTERNAL
FILTER & DRYER

FIGURE III-7

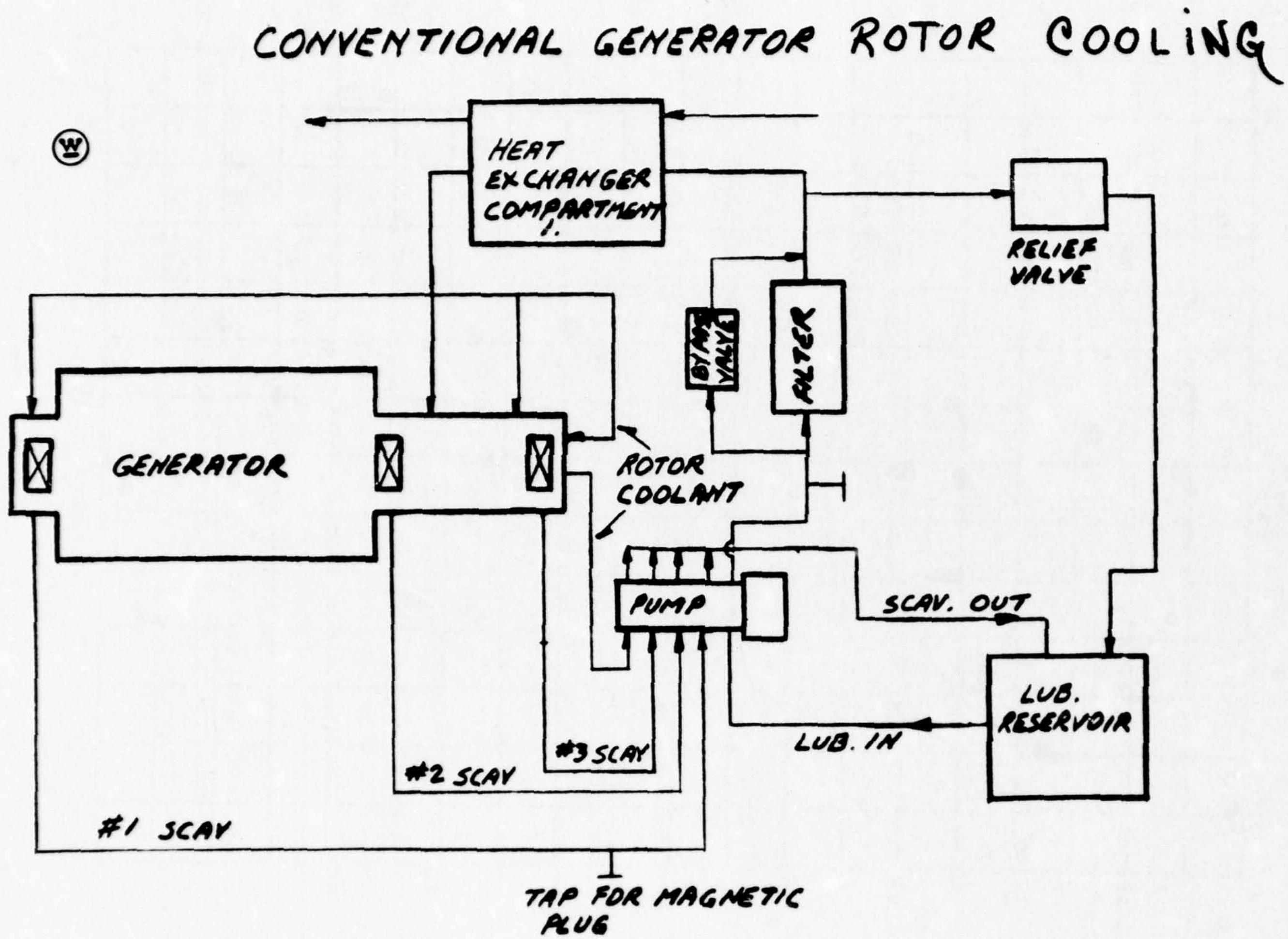

CONVENTIONAL GENERATOR ROTOR COOLING
HEAT EXCHANGER COMPARTMENT
RELIEF VALVE
BYPASS VALVE
FILTER
GENERATOR
ROTOR COOLANT
PUMP
SCAV. OUT
LUB. RESERVOIR
LUB. IN
#3 SCAV
#2 SCAV
#1 SCAV
TAP FOR MAGNETIC PLUG

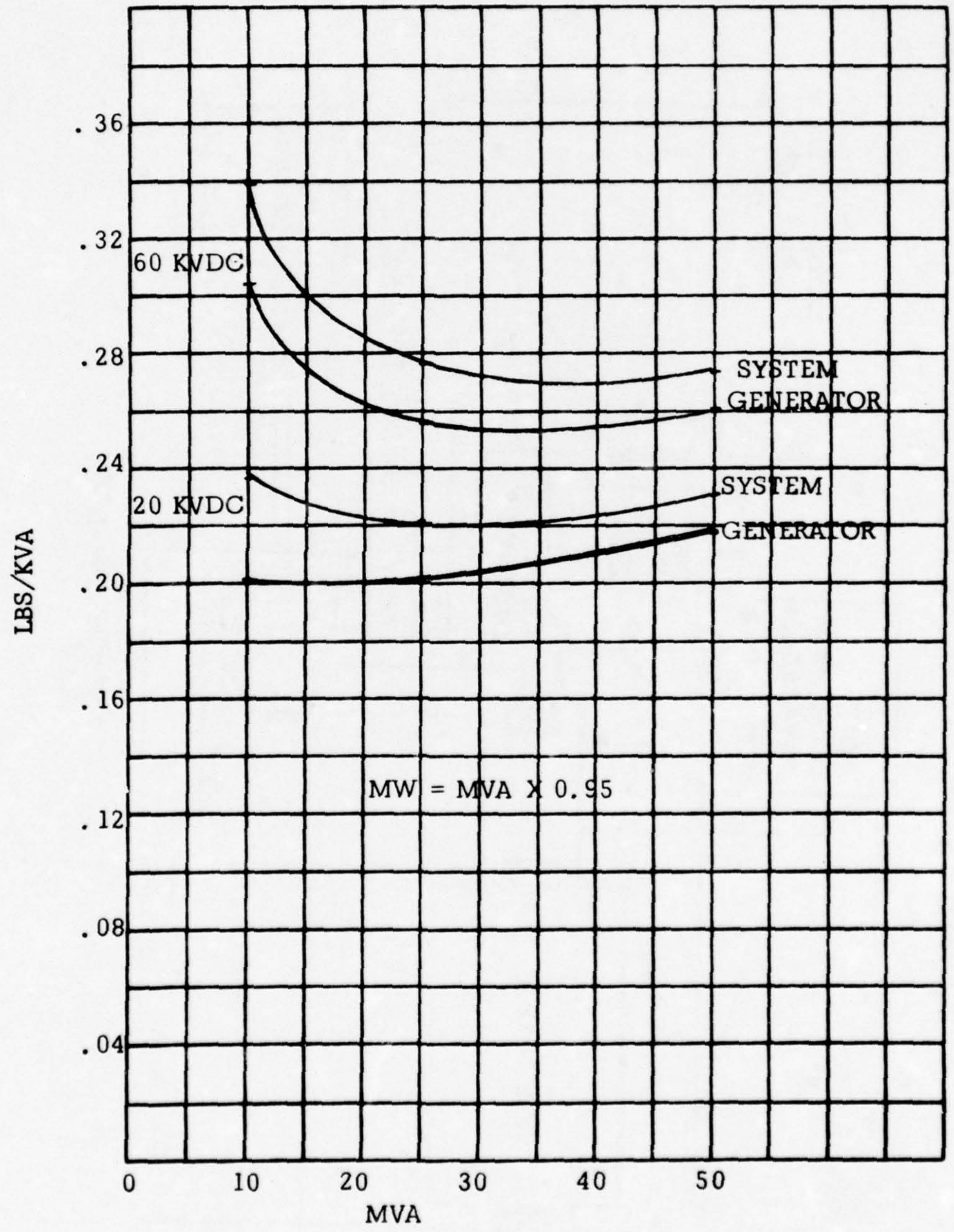
FIGURE III-8

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

SPECIFIC WEIGHT VS MVA

FIGURE III-9

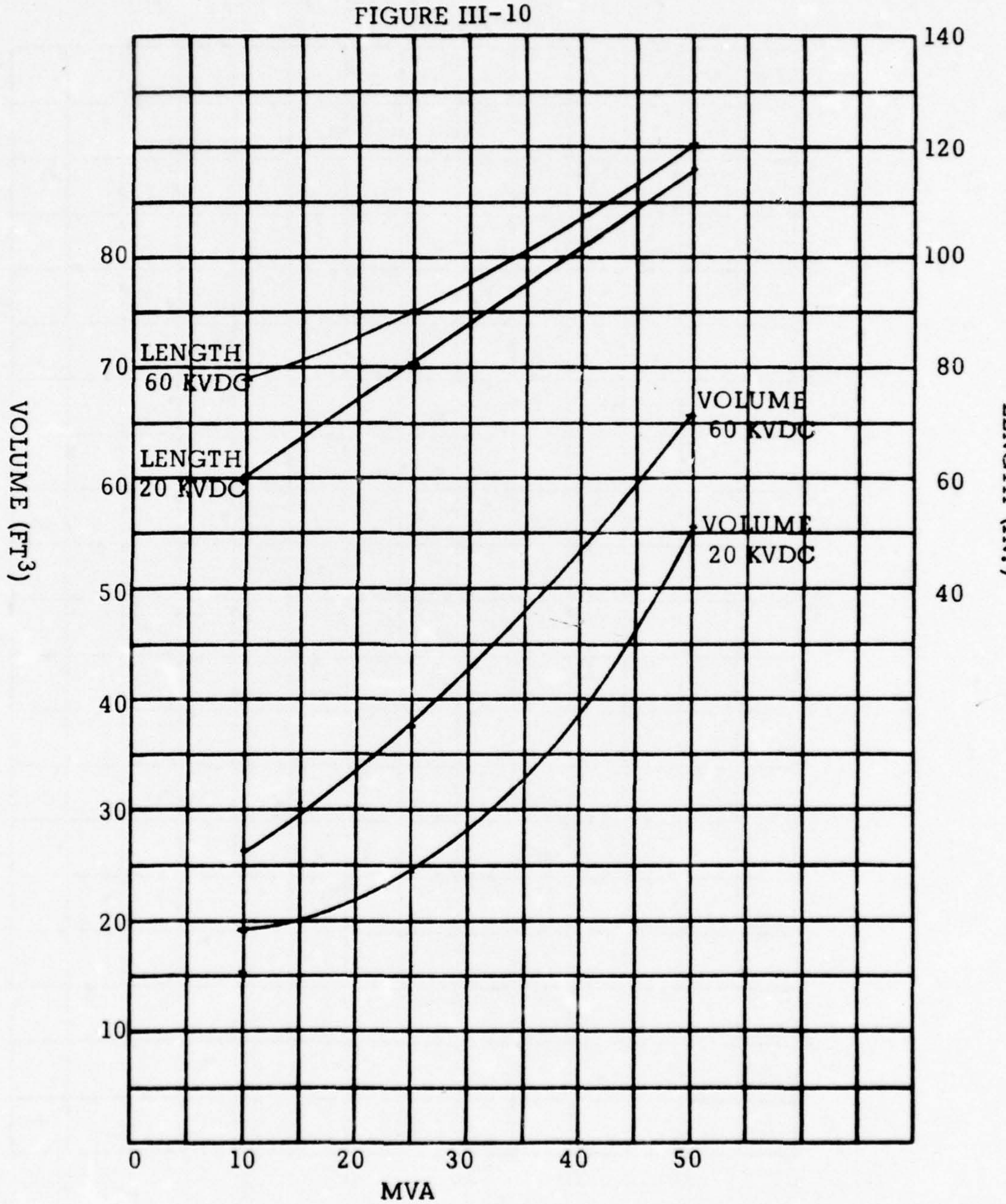


WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

VOLUME, LENGTH VS. MVA

FIGURE III-10



WESTINGHOUSE ELECTRIC CORPORATION

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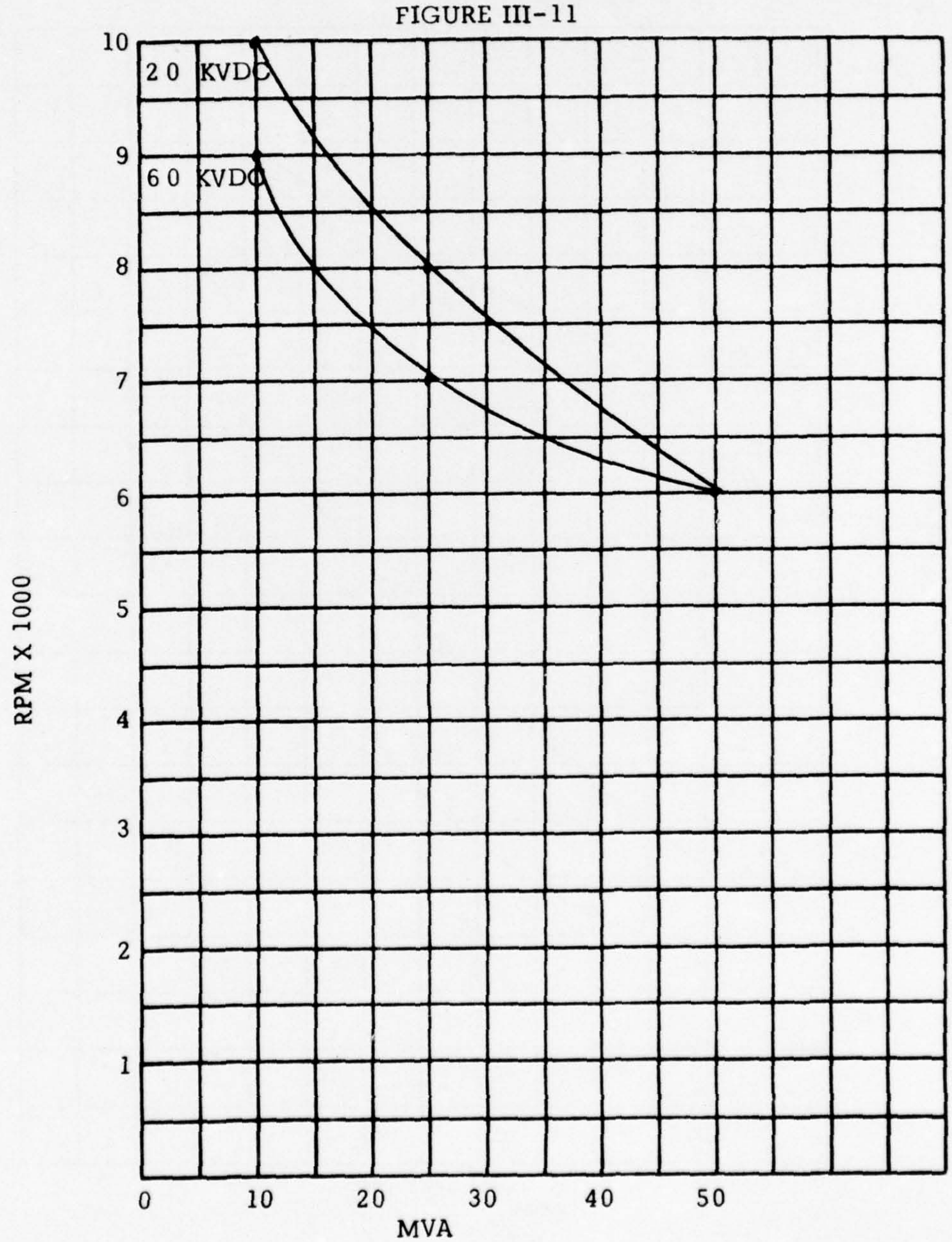
CONVENTIONAL GENERATOR

RPM VS. MVA

FIGURE III-11



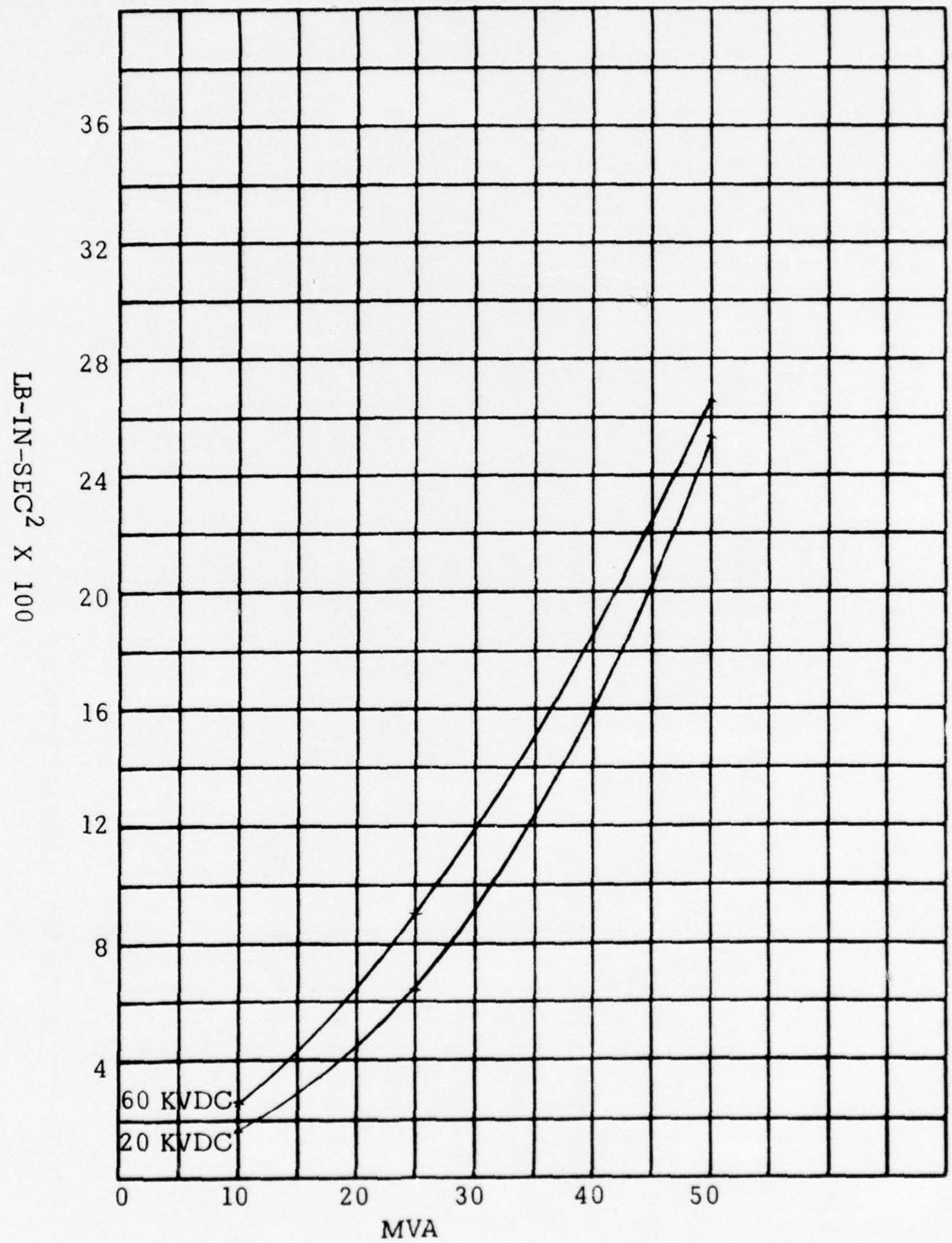
WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

ROTOR INERTIA VS. MVA

FIGURE III-12



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AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

TABLE III-2

SUMMARY OF WEIGHTS

RATING, MVA	10	10	25	25	50	50
VOLTAGE, KVDC	20	60	20	60	20	60
WEIGHTS (LBS)						
ELECTROMAGNETIC	1673	2546	4201	5337	9589	10872
FRAME	337	509	840	1067	1920	2178
*WATER	33	40	56	76	108	130
HOSES & FITTINGS	26.8	26.8	54.4	54.4	96.4	96.4
PUMPS & TANKS	19.4	19.4	39.5	39.5	70.2	70.2
HEAT EXCHANGERS & OIL	270	270	336	336	356	356
TOTAL	2359	3411	5527	6910	12140	13703
LBS/KVA	.236	.341	.221	.276	.243	.274

* TYPICAL FOR 120 SECONDS ON TIME

TABLE III-3

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

POINT DESIGNS

VOLTAGE PARAMETERS AND REACTANCES

RATING, MVA	10	10	25	25	50	50
RPM	10,000	9,000	8,000	7,000	6,000	6,000
POLES	12	14	12	14	16	14
FREQUENCY, HZ	1,000	1,050	800	817	800	700
VOLTAGES, KV	20 DC	60 DC	20 DC	60 DC	20 DC	60 DC
L-L	15.9 AC	47.8 AC	15.9 AC	47.8 AC	15.9 AC	47.8 AC
L-N	9.2 AC	27.6 AC	9.2 AC	27.6 AC	9.2 AC	27.6 AC
LINE CURRENT, AMPS	362	120	905	301.5	1810	603
REACTANCE, PERCENT						
SYNCHRONOUS	208	141	229	210	197	218
TRANSIENT	55	47	55	60	61	60
SUB TRANSIENT	42	40	41	47	42	47

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

TABLE III-4

WEIGHTS FOR POINT DESIGNS

RATING, MVA	10	10	25	25	50	50
VOLTAGE, KVDC	20	60	20	60	20	60
WEIGHT, LBS.						
STATOR						
COPPER	157	160	295	340	486	576
STEEL	178	946	1306	1921	2628	3821
ROTOR						
COPPER	185	245	337	442	652	716
STEEL	854	1195	2263	2654	5824	575
FRAME, BEARINGS, & SHAFT	337	509	840	1067	1920	2178
GENERATOR TOTAL	2011	3055	5041	6404	11510	13050
GENERATOR SPECIFIC WEIGHT, LBS/KVA	.201	.306	.201	.256	.230	.261
ROTOR INERTIA LB-IN-SEC^2	157	257	526	897	2539	2638

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

TABLE III-5

DIMENSIONS

RATING, MVA	10	10	25	25	50	50
VOLTAGE KVDC	20	60	20	60	20	60
DIMENSIONS, INCHES						
FRAME O. D.	21.5	24.5	25.8	30.7	33.2	35.6
STATOR O. D.	19.7	22.5	23.7	28.2	30.5	32.7
ROTOR O. D.	16.27	17.47	19.65	22.5	26.7	27.0
	10.7	12.2	12.7	15.5	18.9	18.5
ACTIVE LENGTH	39.3	51.5	61.6	64.5	95.4	94.0
OVERALL LENGTH	60.5	77.5	81.6	90	116	120
BORE SEAL THICKNESS	.10	.10	.10	.10	.10	.10

TABLE III-6

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

POINT DESIGNS

PARAMETERS FOR CONDUCTORS

RATING, MVA	10	10	25	25	50	50
VOLTAGE, KVDC	20	60	20	60	20	60
POLES	12	14	12	14	16	14
ARMATURE WINDINGS						
CONNECTION	Y	Y	Y	Y	Y	Y
CONDUCTORS PER SLOT	4	12	8	8	4	6
SLOTS	99	75	108	84	132	69
PARALLEL PATHS	1	1	4	1	4	1
PHASE BELT	60°	60°	60°	60°	60°	60°
CURRENT DENSITY ($AMPS/IN^2$)	17,000	17,000	17,000	17,000	17,000	17,000
FIELD WINDINGS						
FIELD CURRENT (AMPS)	200	200	200	200	200	200
CURRENT DENSITY ($AMPS/IN^2$)	15,000	15,000	15,000	15,000	15,000	15,000
MAX. FLUX DENSITY (KL/IN^2)	100	100	100	100	100	100
POWER REQUIRED AT RATED LOAD (KW)	124	162	229	284	442	482

TABLE III-7

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

POWER AND CONTROL OF FIELD

FIELD POWER SOURCE: EXCITER GENERATOR ON SECOND SHAFT OF MAIN MACHINE

EXCITER GENERATOR POWER SOURCE: AUXILIARY POWER FROM AIRCRAFT

RATING, MVA	10	10	25	25	50	50
VOLTAGE, KDVC	20	60	20	60	20	60
MAIN FIELD WINDING POWER (KW)	125	163	229	284	442	482
POWER FOR EXCITER FIELD (WATTS)	2490	3250	4560	5690	8820	9640

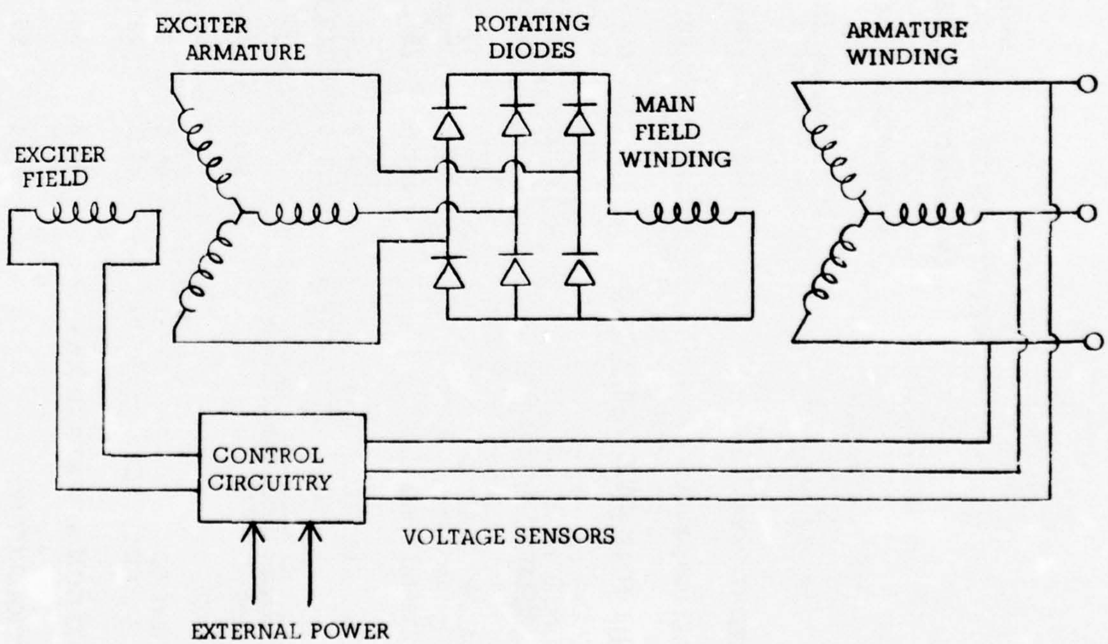


TABLE III-8

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

LOSSES IN POINT DESIGNS

RATING, MVA	10	10	25	25	50	50
VOLTAGE, KVDC	20	60	20	60	20	60
FULL LOAD HEAT LOSSES (KW)						
ROTOR						
POLE FACE	1.34	33.7	3.64	7.06	9.20	23.3
FIELD I^2R	124.5	162.6	228.5	284.5	441.8	482.2
STATOR						
CORE LOSS	35.6	70.4	92.3	147.7	185.7	283.8
ARMATURE I^2R	126.5	127.6	248.5	290.9	488.4	494.4
TOTAL HEAT LOSS (KW)	287.9	364.0	572.9	730.2	1085.1	1283.9
(BTU/SEC)	272.9	345.0	543.1	692.2	1028.7	1217.1
NO LOAD HEAT LOSS (KW)						
ROTOR	14.5	19.7	27.2	35.1	53.7	65.2
STATOR	32.4	63.4	83.0	132.9	167.1	255.4
TOTAL (KW)	46.5	83.1	110.3	168.0	220.8	320.6
(BTU/SEC)	44.1	78.8	104.5	159.3	209.3	304.0
FRICTION & WINDAGE (KW)	44.6	58.1	116.7	78.9	542.0	482.4
EFFICIENCY (%)	97.1	96.3	97.7	97.1	97.8	97.4

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

TABLE III-9

STATOR COOLING

TYPE: THERMAL & FLUID

RATING, MVA	10	10	25	25	50	50
VOLTAGE, KVDC	20	60	20	60	20	60
FULL LOAD HEAT LOSSES (BTU/SEC)	153.7	187.7	223.1	415.8	639	737.7
NO LOAD HEAT LOSSES (BTU/SEC)	30.7	60.1	78.7	126.0	158.4	242.1
HEAT EXCHANGER CAPACITY (NO WATER BTU/SEC)	16.8	32.45	40.78	70.22	82.1	131.16
WATER CONSUMPTION RATE FULL LOAD (LBS/SEC)	.158	.193	.230	.428	.659	.760
WATER CONSUMPTION TOTAL ON TIME						
63 SECONDS		12.159				
64 SECONDS			27.4	27.4		
75 SECONDS					49.5	57
120 SECONDS				51.3	79.8	91.2

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

TABLE III-10

ROTOR COOLING

TYPE: THERMAL AND FLUID						
RATING, MVA	10	10	25	25	50	50
VOLTAGE, KVDC	20	60	20	60	20	60
FULL LOAD HEAT LOSS (BTU/SEC)	119.3	157.3	220.1	276.4	427.5	479.2
NO LOAD HEAT LOSS (BTU/SEC)	13.7	18.7	25.8	33.8	50.9	61.8
WATER CONSUMPTION RATE FULL LOAD (LBS/SEC)	.122	.162	.226	.284	.440	.493
WATER CONSUMPTION (LBS) TOTAL ON TIME						
63 SECONDS		10.2				
64 SECONDS				14.4		
75 SECONDS					33	36.9
120 SECONDS				34.8	52.8	59.2

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

TABLE III-11

PUMPS AND COOLING SYSTEM

SYSTEM	10 MVA	25 MVA	50 MVA
LUBE & ROTOR COOLING			
GPM	65.1	116.5	202.4
$T^{\circ}F$	35	35	35
WEIGHT OF PUMP/TANK, LBS.	8.46	15.1	26.2
VOLUME OF PUMP/TANK, FT^3	.113	.201	.350
WEIGHT OF HOSES & FITTINGS, LBS.	11.7	20.8	36.3
VOLUME OF HOSES & FITTINGS, FT^3	.208	.371	.646
PUMP POWER (KW)	2.15	3.84	6.67
STATOR COOLING			
GPM	57	128	218
$T^{\circ}F$	35	35	35
WEIGHT OF PUMP/TANK, LBS.	10.9	24.4	44.0
VOLUME OF PUMP/TANK, FT^3	.145	.324	.586
WEIGHT OF HOSES & FITTINGS, LBS.	15.1	33.6	60.1
VOLUME OF HOSES & FITTINGS, FT^3	.268	.598	1.08
PUMP POWER (KW)	1.88	4.22	7.20
WATER			
WEIGHT OF PUMP & TANK	8	10	15
WEIGHT OF HOSE & FITTINGS	10	15	25
VOLUME (IN^3)	1300	3000	3700

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION

CONVENTIONAL GENERATOR

HEAT EXCHANGER PARAMETERS

TABLE III-12

RATING, MVA	10	10	25	25	50	50
VOLTAGE, KVAC	20	60	20	60	20	60
HEAT EXCHANGER CAPACITY WITH NO WATER (BTU/SEC)	30.5	51.1	66.5	104	133	192.9
SEA LEVEL, MACH 0.5						
AIR INLET TEMP (^{O}F), SEA LEVEL, HOT DAY	128	128	128	128	128	128
AIR OUTLET TEMP (^{O}F)	210	210	210	210	210	210
AIR FLOW RATE (LB/SEC)	1.59	2.67	3.47	5.43	6.74	10.1
REQUIRED SURFACE AREA $IN^2 \times 10^{-3}$	9.44	15.82	20.59	32.21	41.19	59.52
$\frac{\text{AREA OF AIR SURFACE}}{\text{AREA OF OIL SURFACE}}$	8	8	8	8	8	8
WEIGHT OF DRY HEAT EXCHANGER	24.1	40.4	52.5	82.2	105.7	151.7
VOLUME OF (IN^3) HEAT EXCHANGER	1147	1921	2500	3910	5001	7253
G (AIR) $\frac{LB}{IN^2\,SEC}$	.1	.1	.1	.1	.1	.1
G (OIL) $\frac{LB}{IN^2\,SEC}$	5	5	5	5	5	5
AVERAGE OIL TEMPERATURE	218	218	218	218	218	218
STANDARD DAY 15,000 FT, MACH 0.8						
AIR INLET TEMP (^{O}F)	64.8	64.8	64.8	64.8	64.8	64.8
AIR OUTLET TEMP (^{O}F)	210	210	210	210	210	210
AIR FLOW RATE (LB/SEC)	.787	1.32	1.72	2.68	3.43	4.95
REQUIRED SURFACE AREA ON AIR SIDE $IN^2 \times 10^{-3}$	5.52	9.24	12.02	18.79	24.03	34.86
WEIGHT OF DRY HEAT EXCHANGER	14.0	23.5	30.6	47.8	61.2	88.7
VOLUME OF HEAT EXCHANGER	662.	1109	1443	2257	2886	4185
AVERAGE OIL TEMP (^{O}F)	218	218	218	218	218	218

SECTION III, PARAGRAPH F

CONVENTIONAL GENERATOR

COMPUTER CODE

The object of the computer code is to provide the U.S. Air Force with a method of computing weights and volumes of conventional high power generating systems and to list the auxiliary requirements of the system on the aircraft which employs the system. The input variables allow the user to input any point design in the range of Table I-1, and receive as output the weight, volume, and auxiliary requirements of the specified machine.

The computer code is the result of over 2000 separate computer designs for high power conventional generators. Out of the 2000 designs, six suitable machines were picked at various voltage and power levels to give a good approximation to the weights and volumes of conventional high power special duty cycle machines. The values given in the output of this code are considered to be within 15% of those of an actual system. System weight summaries of the six designs are given in Table III-2.

CONVENTIONAL GENERATOR

COMPUTER CODE

INPUT SHEET

The following parameters must be input to the Westinghouse Conventional Generator Computer Code. They are read in on one data card in F10.4 Formats. The data card should be placed at the back of the deck along with the appropriate control cards for the local computer system.

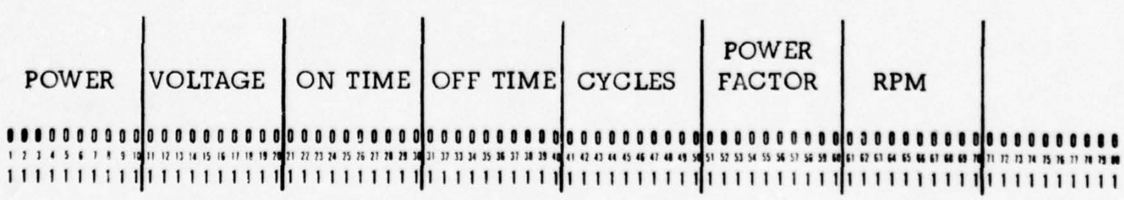
DATA CARD

Parameter	Columns	Units	Range	Sample
POWER	1-10	MW	10-56	25.
VOLTAGE*	11-20	KVDC	20-100	60.
ON TIME	21-30	Seconds	0-99,999	120.
OFF TIME	31-40	Seconds	0-99,999	120.
CYCLES	41-50		0-99,999	1.0
POWER FACTOR	51-60		.9-1.0	1.0
ROTOR SPEED**	61-70	RPM	4,000-11,000	0.0

NOTE: A decimal point must appear in each Input Format Space.

* The AC output voltage is assumed to be rectified to DC, hence the DC units; the weights and volumes do not include the rectifier.

** Should be input as 0. unless a specific RPM is desired.



CONVENTIONAL GENERATOR

COMPUTER CODE

INPUT VARIABLE DEFINITION

POWER	-	The megawatt output of the machine.
VOLTAGE	-	The DC voltage the machine is intended to produce in KVDC; KVDC = 2.17 X KVAC (L-N).
ON TIME	-	The full-load time on the machine per cycle in seconds.
OFF TIME	-	The no-load time per cycle in seconds.
CYCLES	-	The number of cycles per mission.
POWER FACTOR	-	The power factor of the load for the AC machine.
ROTOR SPEED	-	The rotor speed in RPM. If 0 is input, the program will pick the best RPM resulting in the optimum design. If a specific RPM is desired, that RPM should be input and the weight and volume for that specific rpm will be calculated. In general, 4,000-11,000 RPM will work. If the input RPM corresponds to an impractical RPM (machine becomes too long), the computer will state so.

CONVENTIONAL GENERATOR

COMPUTER CODE

OUTPUT VARIABLE DEFINITION

Generator Weight	-	The weight of the generator in pounds, including frame. See attached schematic for view of a typical generator.
Cooling System Weight	-	The weight of the cooling system in pounds, including pumps, hoses, heat exchangers, and circulating fluids. See attached cooling system schematics.
Water Weight	-	The weight of the water in pounds that will be used to cool the heat exchanger under full-load operation.
Generator Diameter	-	The outside diameter of the frame in inches. See attached generator schematic.
Generator Length	-	The length of the generator frame in inches. See attached generator schematic.
Rotor Speed	-	The rated RPM of the machine. If 0.0 is input for RPM, the RPM giving the best weight and volume will be calculated.
Rotor Inertia	-	The inertia of the main rotor and shaft in lb-in-sec^2, excludes exciter rotor and shaft (negligible).
Volume of Heat Exchanger	-	Required volume of heat exchanger in cubic inches given at both sea level and at 15,000 feet.
Auxiliary Requirements	-	System requirements on aircraft.

Coolant Pumps	-	Power to circulate coolant in KW at full-load.
Power for Excitation	-	External power in KW to excite exciter stage of machine at full-load.
Air Flow	-	Air flow in pounds/sec. across heat exchanger when machine is at full-load. Values given at both sea level and 15,000 feet.

CONVENTIONAL GENERATOR

COMPUTER CODE VARIABLE DEFINITIONS

(SEE ATTACHED FIGURES)

USER DEFINED VARIABLES	DEFINITION	UNITS
P	Input Power	Megawatts
V	Input Voltage	KVDC
ON	On Time Per Cycle	SEC
OFF	Off Time Per Cycle	SEC
XN	Number of Cycles	-
PF	Power Factor	-
RPM	Input RPM	RPM

COMPUTED VARIABLES	DEFINITION	UNITS
M	MVA	MVA
V	Voltage Line to Neutral (Redefined from KVDC)	KVAC
RPMC	Computed Value of RPM	RPM
R	Percent Difference Between Input RPM and RPMC	%
FRPM	Weight Adjustment from R	%
GRPMD	Diameter Adjustment from R	%
GRPML	Length Adjustment from R	%
WB	Electromagnetic Weight of Generator as a Function of Power & Voltage	LBS
W	Weight of Generator including frame and RPM Adjustment Factor	LBS
SOD	Stator Outside Diameter	INCHES
ROD	Rotor Outside Diameter	INCHES
RID	Rotor Inside Diameter	INCHES
XLEN	Electromagnetic Length	INCHES
TLEN	Overall Length of Machine	INCHES

COMPUTED VARIABLES	DEFINITION	UNITS
TSOD	Overall Diameter of Machine	INCHES
XI	Rotor Inertia	LB IN SEC^2
CLSWT	Cooling System Weight	LBS
TW	Total Weight of System	LBS
PMPWR	Power to Drive Circulating Pumps (Aircraft Power to — Motors)	KW
EXPWR	Power to Excite Exciter (Aircraft Electrical Power to Machine)	KW
AIRFL	Air Flow Required for Heat Exchanger	LBS/SEC
AIRFLA	Air Flow at 15,000 FEET	LBS/SEC
HC	Heat Capacity of Heat Exchanger	BTU/SEC
HEV	Heat Exchanger Volume	IN^3
HEVA	Heat Exchanger Volume at 15,000 FT	IN^3

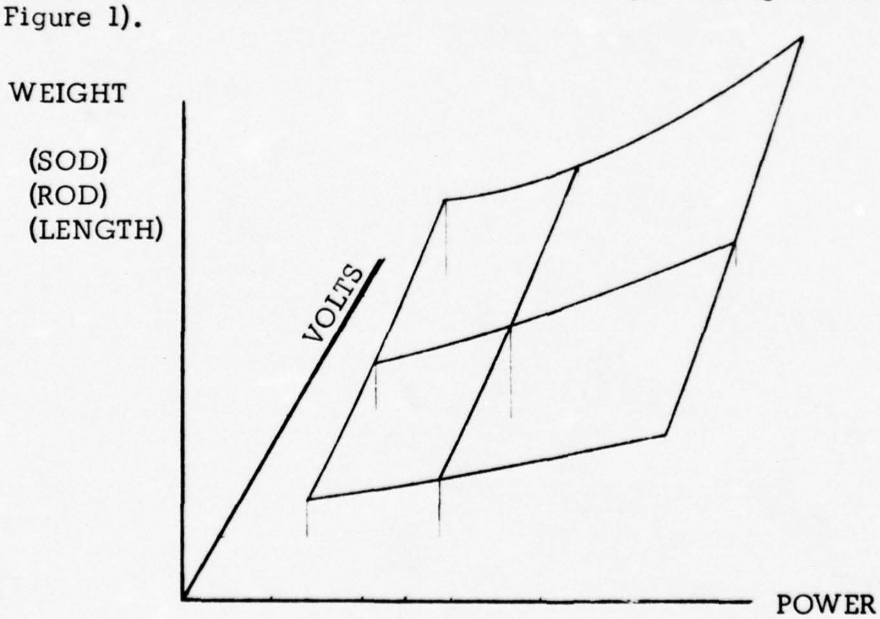
CONVENTIONAL GENERATOR

COMPUTER CODE

DERIVATION OF EQUATIONS

The object of the study was to determine the weight and volume of a high power, high voltage generating system with a special duty cycle. Early in the study, it was determined that the weight and volume of a system is a strong function of power and voltage with minor considerations for other parameters such as duty cycle and RPM. Over 2000 computer designs were made using different combinations of internal parameters to determine the optimum design for machines at several power and voltage levels. In all, nine base designs were made, corresponding to 10, 25, and 50 MVA and 20, 60 and 100 KVDC. It was determined that 100 KVDC was an upper limit for a conventionally wound machine and designs above that voltage were not derived.

Trends were developed between the independent parameters of power and voltage and the dependent parameters of weight, length and diameter. Each of these dependent parameters can be represented by a three dimensional curve with the dependent parameter on the third axis and the independent parameters of power and voltage forming the base plane (see Figure 1).



Empirical equations were formulated to represent the seven dependent parameters of electromagnetic weight, length, stator diameter, rotor outside diameter, rotor inside diameter, heat capacity of heat exchanger and RPM. These equations were found to be:

1. $$\text{EM Weight} = 12.5M \left(\frac{M^2 - 78M + 1521}{V^2 - 80.9V + 1666}\right) + .00649\,(V^2 - 3.96V + 1988)$$

2. $$\text{EM Length} = (-.000968V^2 + .0181V + 1.29)\,(M-37) + 77.5$$

3. $$\text{Rotor Outside Diameter} = .2666M + .125V + 12.48$$

4. $$\text{Rotor Inside Diameter} = .2M + .1333V + 7.57$$

5. $$\text{Stator Outside Diameter} = .333M + .231V + 14.24$$

6. $$\text{Heat Capacity} = 2.5625M + 1.905V - 12.65$$

7. $$\text{RPM} = (.00233\,M^2 - .215M - .075V + 12.96)\,1000$$

Where M = MVA and V = Voltage L-N.

The above equations show machine parameters as a function of MVA and voltage. These equations are valid under the assumption that the RPM calculated in Equation 7 is used. Should the user decide to use a specific RPM more desirable for the overall system, the dependent parameters will change by a percentage corresponding to the percentage change from optimum RPM. The percentage change in parameters is:

8. $$\Delta\,\text{Weight} = .02505\,R^2 - .0227\,R + .457 \quad \%$$

9. $$\Delta\,\text{Diameter} = (-.325 \times 10^{-6})\,R^5 + (.1082 \times 10^{-4})\,R^4$$
$$(.1968 \times 10^{-3})\,R^3 + .0199\,R^2 - 1.06R + .00176 \quad \%$$

10. $$\Delta\,\text{Length} = .0085\,R^2 + 1.548R \quad \%$$

Where R = the percentage change in RPM.

The base parameters given by Equations 1-6 can now be adjusted to fit specific RPM's by multiplying by the factor $1 + \Delta$ (parameter). If the program is allowed to pick its own RPM by setting RPM = 0 in the input, then Δ (parameter) will equal 0.

The best weights and volumes will occur when RPM = 0. Should a lower RPM be desired the machine will be shorter and larger in diameter. If a higher RPM is desired, the machine will be long and thin in order to maintain a 700 Ft. per Sec maximum rotor tip speed. It is possible to input an RPM that will cause the machine to be impractically long. In this case, the program will print out an error code stating so. In general, RPM's in the range of 4,000-11,000 RPM will work.

In the above equations, the electromagnetic sizes only have been determined, but the primary interest is in the overall dimensions. The total weight, diameter and length are a function of the electromagnetic values. These functions are:

$$\text{Weight} = \text{EM Weight} \times 1.2$$

$$\text{Overall Length} = \text{EM Length} + \frac{2}{226}\left(V^2 - 12.12V + 36.7\right) + 19.$$

$$\text{Frame Diameter} = 1.09 \text{ Stator Diameter}$$

The only remaining parameters have to do with the cooling system and external power. Cooling system sizes are a function of MVA and Duty Cycle.

$$\text{Cooling System Weight} = -.043\,M^2 + 7.7M + 263.24$$

$$\text{Water Weight} = \frac{(V-9.2) \times (M \cdot ON \cdot XN)^{.333}}{22.2} + .0174\,(M \cdot ON \cdot XN) + 2.61$$

$$\text{External Power} = .25M + 2$$

$$\text{HEV} = 37.6\ \text{HC}$$

$$\text{AIRFL} = .052\ \text{HC}$$

HEVA = 21.7 HC

AIRFL = .0258 HC

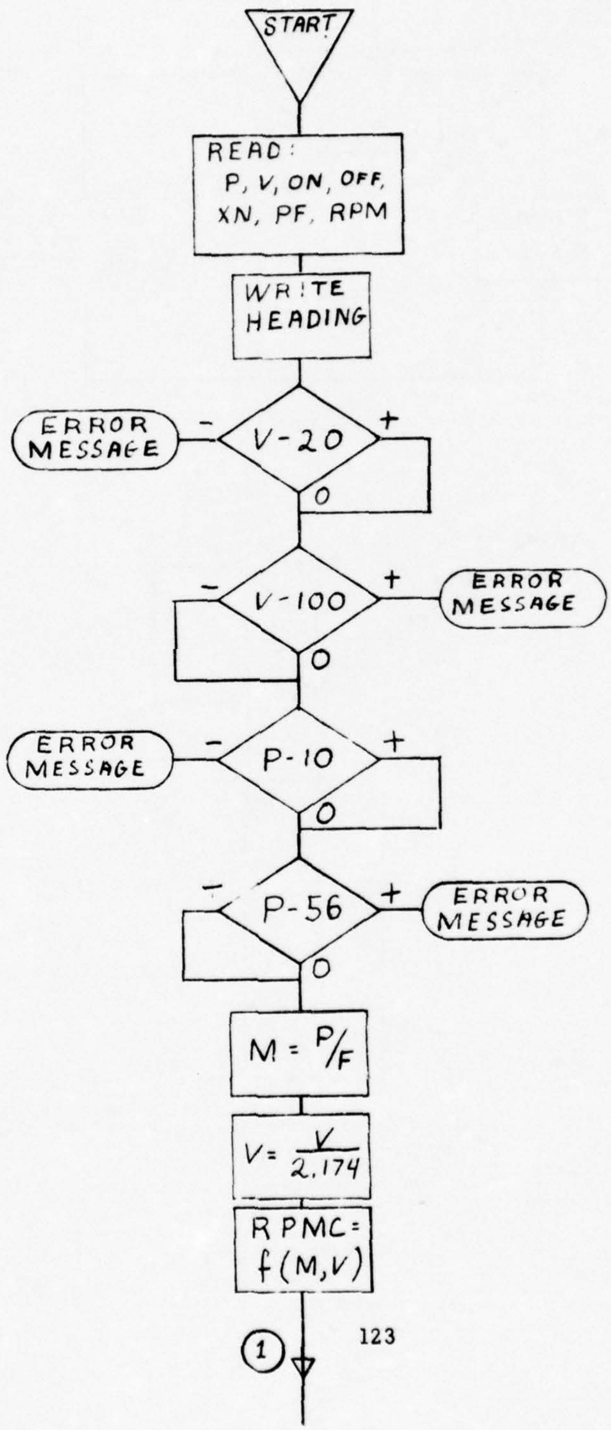
Where HC is the previously computed heat capacity of the heat exchanger, ON is ON TIME, OFF is OFF TIME and XN is the number of cycles.

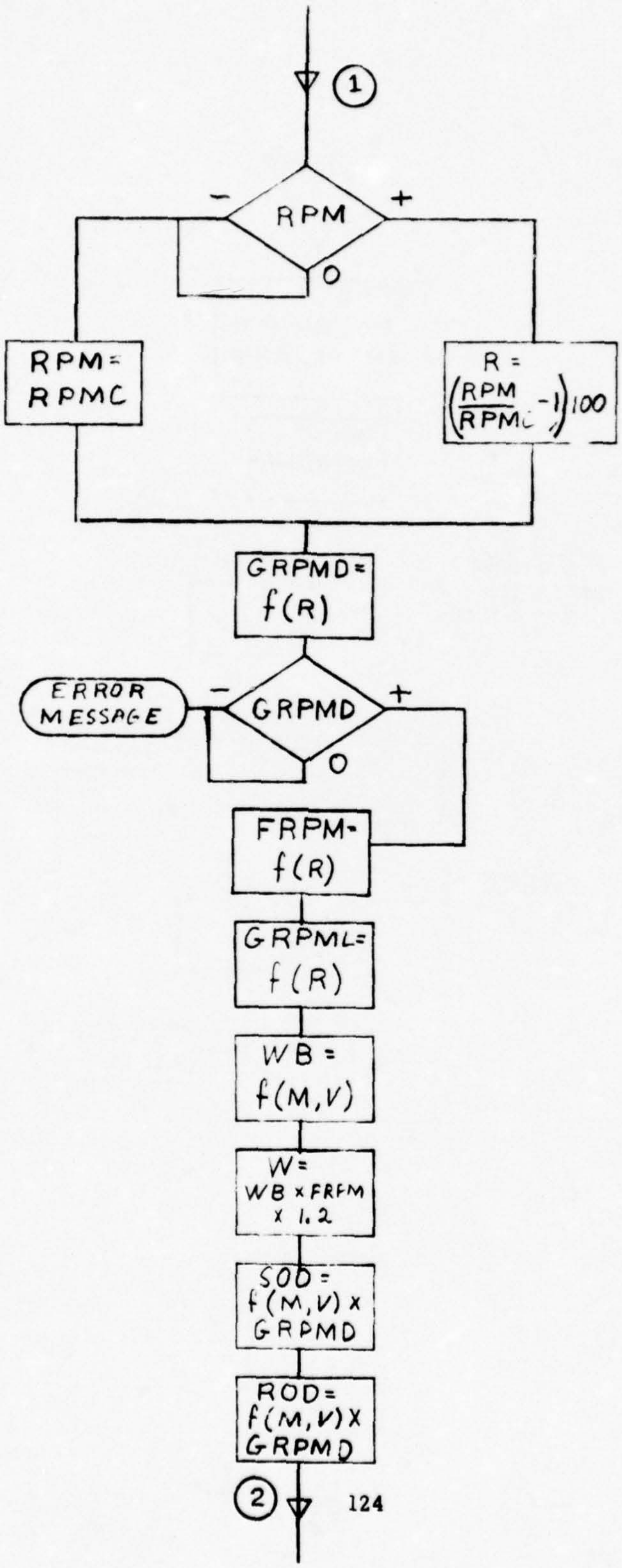
The results of these equations are printed out on the output page generated by the computer code.

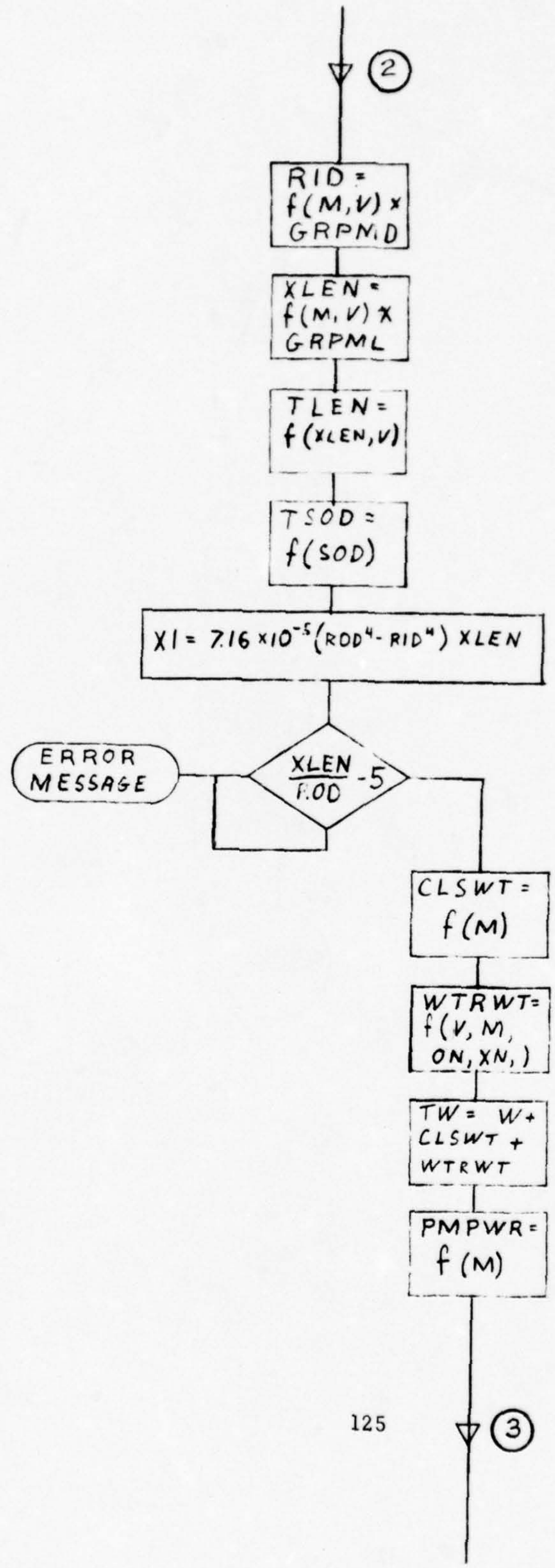
CONVENTIONAL GENERATOR

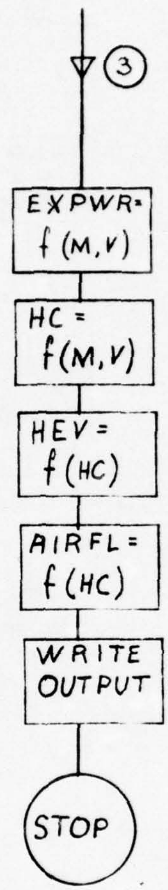
COMPUTER CODE

FLOW DIAGRAM


START
READ:
P, V, ON, OFF,
XN, PF, RPM
WRITE
HEADING
V-20
ERROR
MESSAGE
V-100
ERROR
MESSAGE
P-10
ERROR
MESSAGE
P-56
ERROR
MESSAGE
M = P/F
V = V/2.174
RPMC=
f(M,V)
1


1
RPM
-
+
0
RPM= RPMC
R = (RPM/RPMC - 1)100
GRPMD= f(R)
ERROR MESSAGE
GRPMD
-
+
0
FRPM= f(R)
GRPML= f(R)
WB = f(M,V)
W= WB x FRPM x 1.2
SOD= f(M,V) x GRPMD
ROD= f(M,V) x GRPMD
2


2
RID = f(M,V) x GRPMD
XLEN = f(M,V) x GRPML
TLEN = f(XLEN,V)
TSOD = f(SOD)
XI = 7.16 x 10^-5 (ROD^4 - RID^4) XLEN
ERROR MESSAGE
XLEN/ROD - 5
CLSWT = f(M)
WTRWT = f(V, M, ON, XN,)
TW = W + CLSWT + WTRWT
PMPWR = f(M)
3


3
EXPWR=
f(M,V)
HC =
f(M,V)
HEV =
f(HC)
AIRFL =
f(HC)
WRITE
OUTPUT
STOP

CONVENTIONAL GENERATOR

COMPUTER CODE

LIMITS OF APPLICABILITY

The Program calculates generator weight and volume from empirical formulas based on nine base designs. These designs are intended to cover the range of 20-100 KVDC and 10-50 MVA. No attempt to calculate voltages and powers outside of this range should be made because the formulas are not valid outside of this range. If values outside of this range are input, the program will state so.

Any RPM may be input but, depending upon the other input parameters, the machine may be impractical. If it is, the program will state so. It should be stressed at this point that the machines were designed to generate 9.2, 27.6 and 46 KVAC line to neutral which can be converted to 20, 60, and 100 KVDC directly with no step-up transformer. It should also be cautioned that excessive insulation is necessary for 50 KVDC and above, and that end-turn development must be done on these higher voltage machines.

CONVENTIONAL GENERATOR

COMPUTER CODE

APPENDIX 1

LISTING AND SAMPLE OUTPUT

```
DOS FORTRAN IV 360N-FO-479 3-8          MAINPGM          DATE   01/21/76      TIME     16.21.22

          REAL M
          READ(1,5)P,V,ON,OFF,XN,    PF,RPM
    5     FORMAT(7F10.4)
          WRITE(3,3)
    3     FORMAT('1 COVENTIONAL GENERATOR, WESTINGHOUSE ELECTRIC CORP.'/////)
          WRITE(3,6)
    6     FORMAT( '     POWER      VOLTAGE    ON TIME    OFF TIME   CYCLES     PF
         1          RPM'/)
          WRITE(3,7)P,V,ON,OFF,XN,    PF,RPM
    7     FORMAT(1X,8F10.4,/////)
          IF(V-20.)15,10,10
   10     IF(V-100.)25,25,15
   15     WRITE(3,20 )V
   20     FORMAT('  VOLTAGE MUST BE IN RANGE 20 - 100 KVDC'/' INPUT VOLTAGE
         1=',F10.4,'KVDC')
          GO TO 85
   25     IF(P-10.)35,30,30
   30     IF (P-56.)45,45,35
   35     WRITE(3,40)P
   40     FORMAT('  POWER MUST BE IN RANGE 10 - 50 MW.'/'INPUT POWER =',
         1F10.4,'MW')
          GO TO 85
   45     M=P/PF
          V=V/2.174
          RPMC=(.002336*M**2-.215*M-.075*V+12.96)*1000.
          IF(RPM)50,50,55
   50     RPM=RPMC
   55     R=(RPM/RPMC-1.)*100.
          GRPMD=1.+(.17566E-02-1.06183*R+.199633E-01*R**2+.196861E-03*R**3-.
         1108234E-04*R**4-.32481324E-06*R**5)/100.
          IF (GRPMD)65,65,56
   56     FRPM=1.+(.45710-.22704E-01*R+.25055E-01*R**2)/100.
          GRPML=1+(.0085*R**2+1.548*R)/100.
          WB=12.5*M*((M**2-78.*M+1521.)/(V**2-80.9*V+1666.)+.64903E-02*(V**2
         1-3.96*V+1988.))
          W=WB*FRPM*1.2
          SOD=(.333*M+.231*V+14.24)*GRPMD
          ROD=(.2666*M+.125*V+12.48)*GRPMD
          RID=(.2*M+.1333*V+7.57)*GRPMD
          XLEN=((1.29+.0181*V-.9687E-03*V*V)*(M-37.)+77.5)*GRPML
          TLEN=XLEN+2./226.*(V*V-12.12*V+36.7)+19.
          TSOD=1.09*SOD
          XI=7.16 E-05*XLEN*(ROD**4-RID**4)
          IF(XLEN/ROD-5.)75,75,65
   65     WRITE(3,70)
   70     FORMAT(1X'MACHINE IS TOO LONG.  TRY A LOWER RPM.')
          GO TO 85
   75     CLSWT=263.24+7.7*M-.043*M**2
          WTRWT=(V-9.2)*(M*ON*XN)**.3333/22.2+.0174*M*ON*XN+2.61
          TW=W+CLSWT+WTRWT
          PMPWR=.25*M+2
          EXPWR=.168*M+.44+.038*(V-9.2)
          HC=2.5625*M+1.905*V-12.65
          HEV=37.6*HC
          AIRFL=.052*HC
          HEVA=21.7*HC
          AIRFLA=.0258*HC
          WRITE(3,80)W,CLSWT,WTRWT,TW,TLEN,TSOD,RPM,XI,HEV,HEVA,PMPWR,
```

```
                     1EXPWR,AIRFL,AIRFLA
0054        80        FORMAT(1X////,' GENERATOR WEIGHT             'F10.4,'LBS'//        056
                     11X,'COOLING SYSTEM WEIGHT        'F10.4,'LBS'/  /                  057
                     11X,'WATER EXPENDED               'F10.4,'LBS'//                    058
                     11X,'TOTAL SYSTEM WEIGHT          'F10.4,'LBS'//                    C59
                     11X,'GENERATOR LENGTH             'F10.4,'INCHES'/          /       060
                     11X,'GENERATOR DIAMETER           'F10.4,'INCHES'//                 061
                     11X,'ROTOR SPEED                  'F10.4,'RPM'//                    062
                     11X,'ROTOR INERTIA                'F10.4,'LB-IN-SEC-SEC'//          063
                     11X,'HEAT EXCHANGER VOLUME        'F10.4,'CUBIC INCHES AT SEA LEVEL
                     1 '10X,F10.4,' CUBIC INCHES AT 15000 FT'//
                     11X,'AUXILIARY REQUIREMENTS       '//                               065
                     11X,'      COOLANT PUMPS          'F10.4,'KW'//                     066
                     11X,'      POWER FOR EXCITATION   'F10.4,'KW'//                     067
                     11X,'      AIR FLOW               'F10.4,'LBS PER SEC AT SEA LEVEL
                     1 '10X,F10.4,' LBS PER SEC AT 15000 FT')
0055        85        CONTINUE                                                           069
0056                  CALL EXIT                                                          C70
0057                  END                                                                071
```

CCVENTIONAL GENERATOR, WESTINGHOUSE ELECTRIC CORP.

POWER	VOLTAGE	ON TIME	OFF TIME	CYCLES	PF	RPM
25.0000	60.0000	120.0000	0.0	1.0000	1.0000	7500.0000

GENERATOR WEIGHT	6919.4023LBS	
COOLING SYSTEM WEIGHT	428.8647LBS	
WATER EXPENDED	66.7598LBS	
TOTAL SYSTEM WEIGHT	7415.0234LBS	
GENERATOR LENGTH	95.8556INCHES	
GENERATOR DIAMETER	29.3945INCHES	
ROTOR SPEED	7500.0000RPM	
ROTOR INERTIA	749.8237LB-IN-SEC-SEC	
HEAT EXCHANGER VOLUME	3909.9617CUBIC INCHES AT SEA LEVEL	2256.5474 CUBIC INCHES AT 15000 F
AUXILIARY REQUIREMENTS		
COOLANT PUMPS	8.2500KW	
POWER FOR EXCITATION	5.3392KW	
AIR FLOW	5.4074LBS PER SEC AT SEA LEVEL	2.6829 LBS PER SEC AT 15000 FT

SECTION IV

COMPARISONS, CONVENTIONAL VS. SUPERCONDUCTING GENERATORS

As indicated throughout the prior two sections, the weights of the superconducting generator and its supporting system are significantly less than conventional generators. This was first summarized in Figure III-2 for increasing voltage at a given output; Figure IV-1 further highlights this for increasing output at a given voltage. To further emphasize this difference, recall that the conventional generator data represents well known state-of-the-art technology pushed to the very limits ("coffin corner" designs). On the other hand, the approaches used on the superconducting designs were one of conservatism, i.e., using only the limited state-of-the-art that has been proven to date. Had more advanced superconducting materials been used or had higher tip speeds or higher flux densities been allowed in the rotor, significant weight reductions (nearly halved) could have been achieved as illustrated in Figures IV-2 and IV-3.

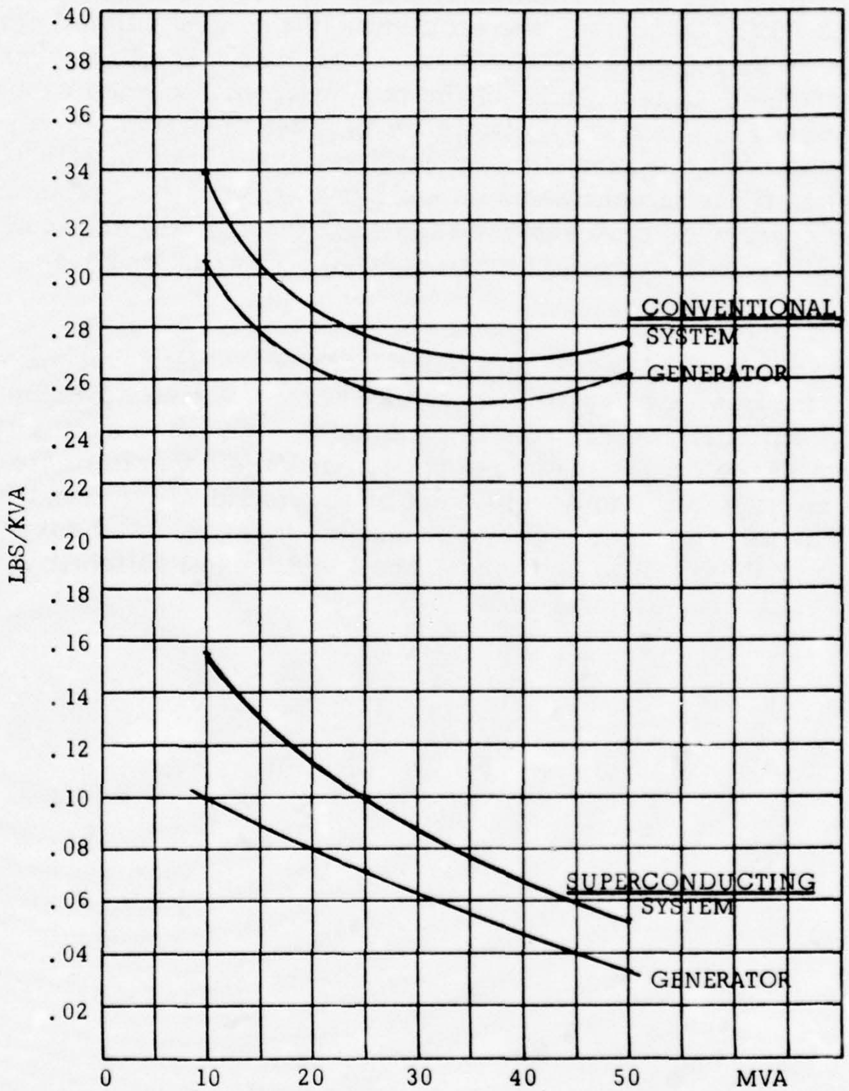
Of course, an added feature which the superconducting generator with the Gramme ring has over the conventional generator is the "no-limit" choice of voltage. The need for any output transformer is literally done away with by using the Gramme ring winding, and, because of the necessary long stacks of the conventional generators, its applicability appears confined to the superconducting generator.

It is recognized that minimum weight and volume do not necessarily make the best system, and because of that possibility, various other conditions of comparison were analyzed and are summarized in Tables IV-1 through IV-6. In Table IV-1, note that the admitted longer startup times of the superconducting machines are counterbalanced by the longer, controlled shutdown times required for the long-shaft conventional generators. An uncontrolled shutdown of the latter would lock thermal distortions into the shaft that could only be worked out of the rotor via a very long, carefully controlled restart (of several hours, if not days).

As seen on Table IV-3, the projected cost per mission is actually less for the superconducting generator. In particular, the helium cost can be less than the increased turbine fuel-consumption cost that occurs as a result of the conventional generator having lower efficiency, e.g., 95% vs. 99%. Of course, the efficiency of the conventional generator can easily be increased a couple of points, but only at noticeable weight gain expense. In fact, most of the conventional designs of the study were optimized around 97% efficiency in order to minimize total system (fuel) weight at the expense of generator weight. The development costs of the two types of generators as well as their projected production recurring costs were also analyzed in detail (not shown) and found to be within 10 percent of each other indicating no particular advantage either way.

In summary, the comparisons generally indicate that the superconducting generator systems have significant overall advantages over the conventional generators. In conclusion, it is also worthy of note that two of the worlds leading suppliers of large generators are presently firmly committed to the development of superconducting machines for central power stations, simply because of their projected advantages of lower cost (both initial and operational) and greater reliability over today's proven conventional generators.

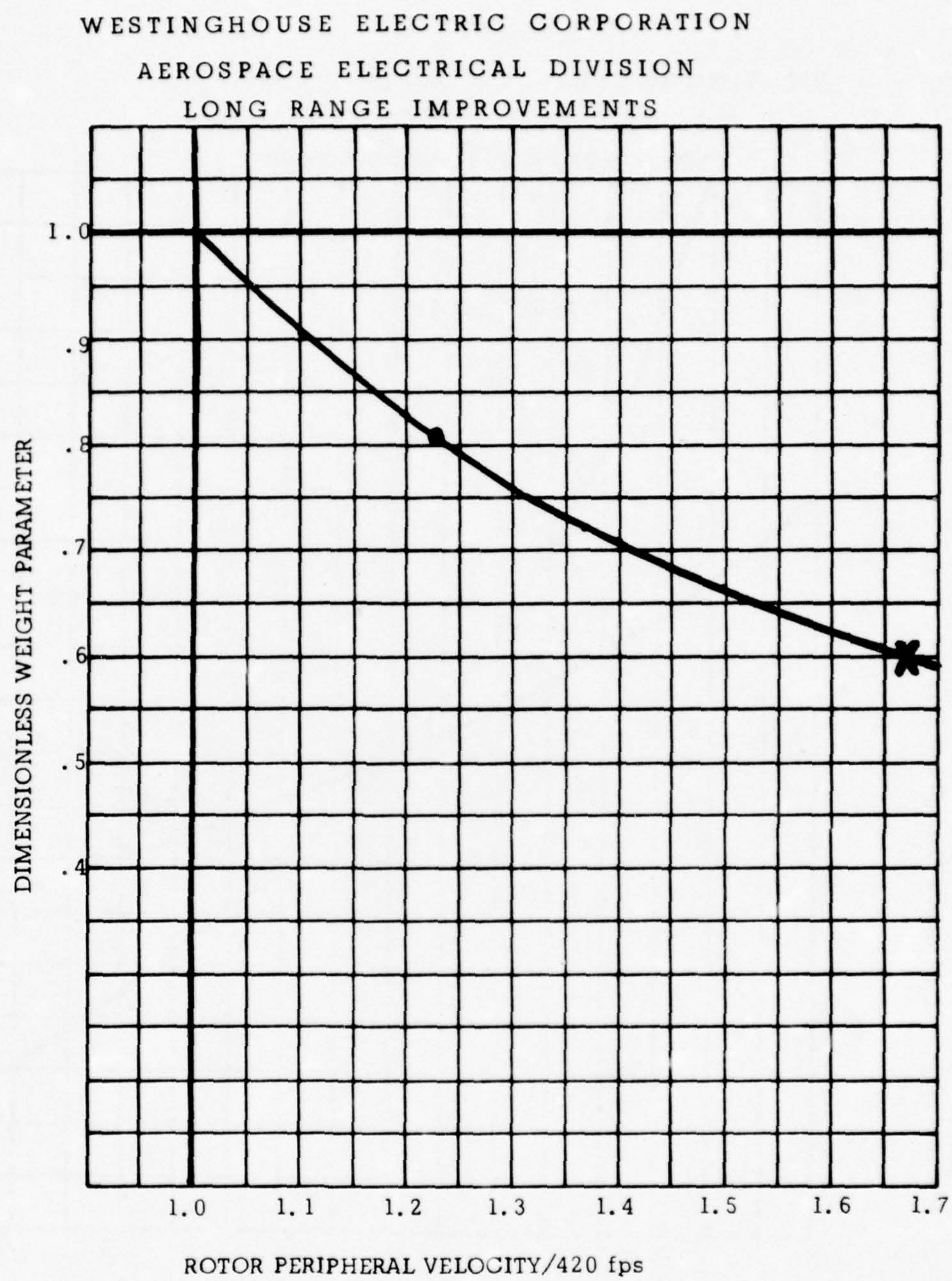
WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION
HIGH POWER STUDY
COMPARATIVE HIGHLIGHTS - SPECIFIC WEIGHT VERSUS MVA



60 KVDC

120 SECONDS ON TIME

FIGURE IV-1



● DENOTES ALUMINUM, NIOBIUM, TITANIUM WIRE

X DENOTES VELOCITY OF CONVENTIONAL GENERATOR

FIGURE IV-2

WESTINGHOUSE ELECTRIC CORPORATION
AEROSPACE ELECTRICAL DIVISION

FIELD STRENGTH PARAMETER

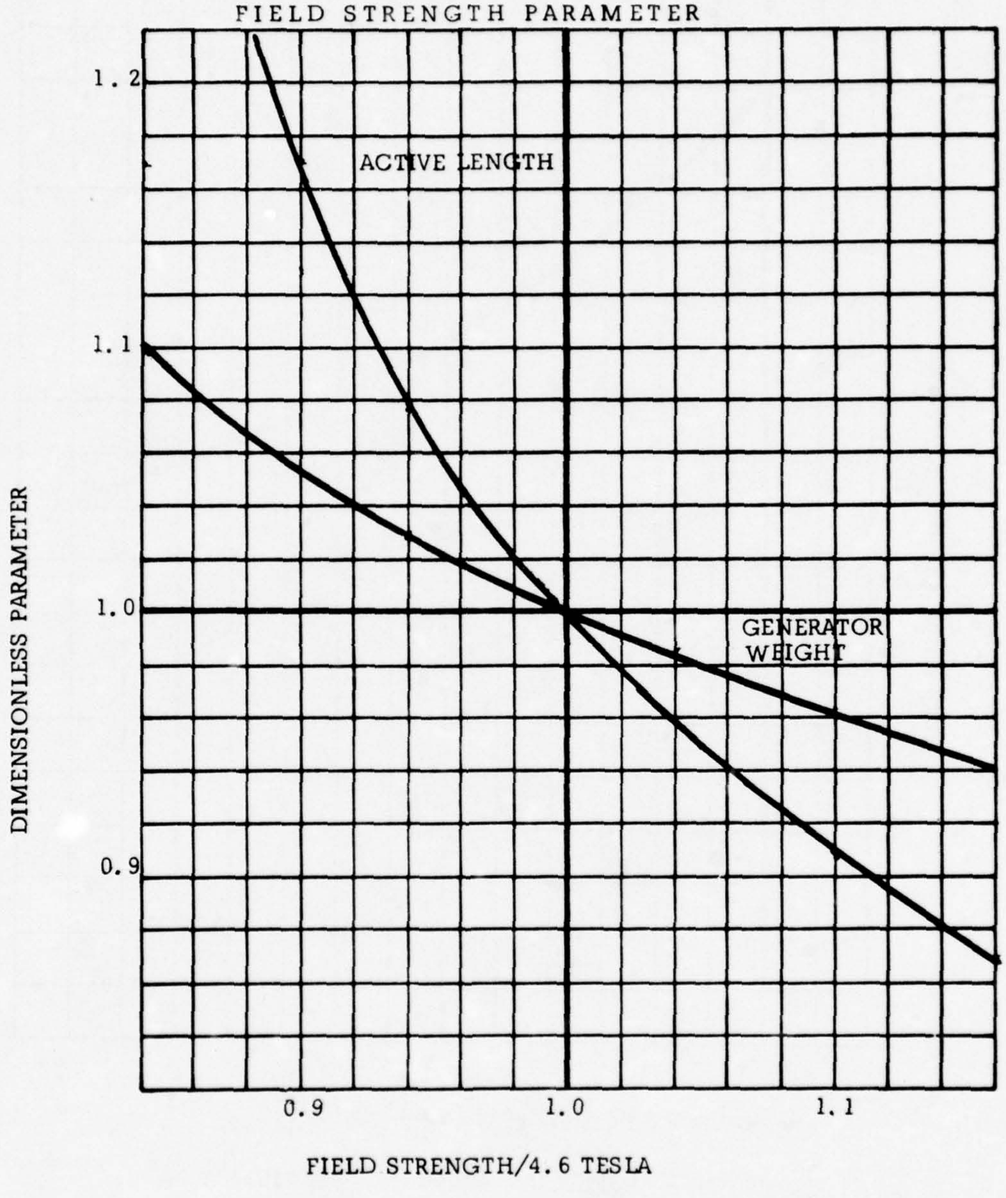


FIGURE IV-3

TABLE IV-1

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

HIGH POWER STUDY

OPERATIONAL SUITABILITY
(25 MVA, 6800 RPM, 60 KVDC)

	CONVENTIONAL	SUPERCONDUCTING
• RESTARTABILITY/SHUTDOWN	CAREFUL CONTROL REQ'D	ROUTINE
• TURNAROUND TIME	N/A	$<$1 HR. HE REFILL
• STARTUP TIME - COOL DOWN - SHAFT ACCEL. - EXCITE	N/A $\sim$3 SEC $<$1 SEC	1.7 HOURS $\sim$3 MINUTES $\sim$1 MINUTE
• NON-CONTINUOUS OUTPUT/RPM DROOP	MAY REQUIRE IDLING	ALWAYS AT IDLE, READY
• OFF DESIGN OPERATION	FLEXIBLE DOWNWARD	FLEXIBLE UP OR DOWN
• PERFORMANCE DEGRADATION WITH TIME	ROTOR BALANCE	HE SEALS
• COMPONENT SYSTEM MAINTAINABILITY	SEALS, BRGS., STATOR OIL	SAME PLUS BRUSHES
• GROUND CHECKOUT (PERIODIC)	STATOR OIL & INSULATION ROTOR BALANCE	STATOR OIL & INSULATION HE SEALS VACUUM INTEGRITY BRUSH WEAR
• SIGNATURE	STEAM	STEAM
• RELIABILITY	"COFFIN CORNER"	CONSERVATIVE

TABLE IV-2

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

HIGH POWER STUDY

AIRCRAFT INTERFACE

(25 MVA, 6800 RPM, 60 KVDC)

	CONVENTIONAL	SUPERCONDUCTING
EXHAUSTING GASES	STEAM	STEAM, HE GAS
AIRCRAFT POWER REQUIREMENTS - Clutch Losses, Pumps	8 KW	16.7 KW
- Excitation	5.7 KW	0.5 KW
HEAT REJECTION - CONTINUOUS	N/A	79.2 KW
- INTERMITTENT	810 KW	249 KW
EMI	SHIELDED	SHIELDED
VIBRATION	TYPICAL WOUND ROTOR COIL SHIFTING PLUS SHUTDOWN	MINIMAL
STRUCTURAL MOUNTING	TRACK/RAIL SUSPENSION	C. G. YOKE
STATOR OIL CONDITIONER	CART OR ON A/C	CART OR ON A/C
ROTOR COOLANT	ENLARGED LUBE SYS.	HE REFRIGERATOR ON CART OR ON A/C; HE DEWAR ON A/C

TABLE IV-3

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

HIGH POWER STUDY

ESTIMATE OF OPERATIONAL COSTS - DOLLARS PER MISSION

(25 MVA, 6800 RPM, 60 KVDC)

	CONVENTIONAL	SUPERCONDUCTING
. GROUND STANDBY - 70°K, LN_2 REFRIG.	N/A	NIL
. COOLDOWN TO 4.2°K, 44 LITERS HE	N/A	$ 90
. HOLD AT 4.2°K, 10 HOURS, 170 LITERS HE	N/A	$ 340
. ENGINE FUEL FOR MOTORING	N/A	$ 22
. EXPENDABLES, 120 SEC - HELIUM	N/A	INCLUDED ABOVE
- COOLING FLUID	NIL	NIL
- EXCITATION POWER	NIL	NIL
- PUMP POWER	NIL	$ 2
(FOR 4 POINTS IN EFF.) - FUEL	$1,230	BASELINE
. MAINTENANCE/SERVICE REQUIREMENTS	$ 110	$ 110
. DEPRECIATION, COMPONENTS REPLACEMENT	$3,000*	$ 740**
TOTAL	$4,340	$1,304

* UNIT COST ÷ 100

** REQUIRES HE SEAL REPLACEMENT AND BRUSH REPLACEMENT EVERY 100 MISSIONS FOR $2K. ASSUMED 5:1 INCREASE IN USABLE MISSIONS DUE TO HIGHER RELIABILITY BUILT INTO DESIGN.

TABLE IV-4

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

HIGH POWER STUDY

SAFETY	CONVENTIONAL	SUPERCONDUCTING
• COMBUSTION PROBLEM	NONE	NONE
• CONTAINMENT	MARGINAL: HIGH TIP SPEED & KE	OK
• FAULTS - EXTERNAL & INTERNAL	CRITICAL, TBD	CRITICAL, TBD
• ELECTRICAL SHOCK	ENCLOSED & GROUNDED	ENCLOSED & GROUNDED
• SHUTDOWN	CONTROLLED DECEL & THERMAL SOAK-BACK	COAST OK

TABLE IV-5

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

HIGH POWER STUDY

GROUND SUPPORT	CONVENTIONAL	SUPERCONDUCTING
. CRYOGENS	N/A	CLOSED LN_2 SYSTEM
. STAND BY POWER REQUIREMENTS	NONE	UTILITY ELEC POWER
. SPECIAL PERSONNEL REQUIRED	TECHNICIANS	TECHNICIANS
. STATOR OIL CONDITIONER	DRYER/FILTER	DRYER/FILTER
POWER CONDITIONING COMPLEXITY	NONE FOR HI VOLTAGE,	NONE DUE TO VOLTAGE
	TRANSFORMER IF LOW VOLTAGE	NATURALLY LOW Xd"
	REGULATED OUTPUT	CAN BE SLOWLY REGULATED

TABLE IV-6

WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

HIGH POWER STUDY

CONTRIBUTION TO TECHNOLOGY

	CONVENTIONAL	SUPERCONDUCTING
• IMPROVEMENT POTENTIAL	NIL	HALF WEIGHT/VOLUME 3 X VOLTAGE LOWER COST
• CONTRIBUTION TO NON-SLTDP	NONE	FUSION CENTRAL STATION HI VOLTAGE UTILITY GRID NAVY PROPULSION HIGH SPEED TRANSPORTATION M H D MAGNETS SUPERCON MATERIALS DEV. ETC.
• FEEDBACK TESTING SETUP	POTENTIAL TEST BED FOR SCR & VACUUM SWITCHES	

SECTION V

HIGH POWER LIGHT WEIGHT MHD GENERATORS

A. Past Experience in Rocket Driven MHD Generators

Westinghouse interest in short burst generator systems goes back to the early 1960's. In 1962 a study was made on solid propellant systems with the assistance of Atlantic Research and Hercules. The MHD power produced was intended to drive arc heaters for periods of one to five minutes. Atlantic proposed a gel burning motor with compounds of $CsNO_3$; Al and $CrClO_4$; Al. Hercules proposed both solid propellant and hybrid systems. The composition of the solid propellant was considered classified but it was said to be capable of producing 7000°F working gas. The hybrid system used $LiAlH_4(CH_2)_x$ or similar compounds with an N_2O_4 oxidant. It had an advantage over the solid system in controllability and the ability to operate in multiple start/stop service.

Later in the year the study was extended to consider systems for size ranges from one to 600 megawatts and operating times up to five minutes. Liquid engine information was supplied by Rocketdyne. Several systems were worked out and the MHD generators sized. A solid propellant system required a grain 20' in diameter and 37' long to produce 600 MW for five minutes. Rocketdyne proposed using six H-1 engines, three E-1 engines, or one F-1 engine burning kerosene and LOX. Size and weight were not a consideration and as a result the MHD generator type selected was a conservative subsonic design, operating in a Faraday mode at 3000 volts. In some cases the channel dimensions reached six feet square by 50 feet long.

B. Recent Considerations for a Light Weight Channel

The most obvious approach to weight reduction in an MHD channel is to remove as much mass as possible. One way to accomplish this is to substitute thin wall tubing for machined cooling rings used in electrode fabrication. Not only is weight removed but shaped tubes are less costly than machined rings.

When compression gas seals are used, one place to reduce weight is in the tie rods and flanges which comprise the cooling rings to form the gas seal. By substituting fiberglass reinforced epoxy shell for the flange-tie rod arrangement and combining with the thin wall cooling tubes, an effective weight reduction is accomplished.

However, several problems remain. For example each electrode has a cooling tube, and each end of the tube must be sealed as it passes through the epoxy shell. Then each end of the cooling tube must be connected to a cooling manifold. A 100-electrode generator channel contains a great number of potential leaks. In addition, this arrangement does not reduce the weight of the water required for cooling.

An approach which eliminates some of these problems is to apply ablative cooling techniques developed for space applications. Pyrolytic graphite is used on reentry vehicles to prevent overheating. When the graphite becomes hot, it ablates, or flakes off, carrying the heat with it. This, by its nature, makes the graphite coating expendable. Consequently if this technique is used in an MHD channel and diffuser, the graphite would have to be periodically replaced.

Furthermore, graphite has a high thermal conductivity and will transmit excessive quantities of heat to the outer shell and support structure. This necessitates that the shell be made of high temperature materials. Should epoxy shells be considered for this application, the danger exists of heat distortion and damage during firing.

Another approach is a gas-cooled MHD generator that uses transpiration cooling. The insulator rings in this construction are fabricated from porous ceramics. A positive pressure of cooling gas, such as nitrogen oxygen, CO_2, or air, is maintained behind the porous insulators. The cooling gas flows through the insulators, into the MHD channel, thereby forming a cool layer along the walls of the channel. A number of porous materials, particularly aluminum oxide, are available commercially for this application.

Lightweight high temperature materials can be used throughout, including the pressure shell. Water connections for each electrode are eliminated, large volumes of cooling water are not required, and the sytem can be simply assembled from readily available materials.

C. Preferred Solution

The gas-cooled MHD channel and diffuser are the preferred solution for an airborne MHD power source. The construction of a channel and diffuser suitable for test in the Air Force's MHD facilities at Wright-Patterson AFB is shown in Figures V-1 and V-2.

The channel design is circular in cross section and is made up of alternating electrodes and insulators. The electrodes are slanted along equipotential lines and are composed of either calcia or ceria stabilized ZrO_2. An Inconel screen is imbedded within the ZrO_2 to act as a current carrier. Power terminations are made at the end electrodes only.

The insulators are cut from commercially available ceramic tubing. Aluminum oxide tubes can be obtained with a void fraction as high as 25%. This high porosity allows for adequate cooling gas to flow into the plasma to keep the walls cool and also enhances the ability of the insulator to withstand thermal shock. The thermal conductivity of porous materials is also lower than that of dense materials. This material can be used to 1900°C. Initially the porous Al_2O_3 spacer rings will be cut from varying diameter tubes and shaped to size.

When the electrodes and insulator rings are fabricated they will be assembled on a mandril and cemented together with an alumina or zirconia cement, forming an integral unit.

The cooling gas is supplied to the backs of the insulator rings through the corrugated alumina ceramics. Gas is introduced into a pentenum at the upstream end of the channel and flows down the openings between the corrugations. The gas can also flow between the corrugations. The webbing from which the corrugations are formed is also porous.

The corrugated ceramic material, usable to 1200°C, is rolled and cut to the desired configuration. Typically material with five corrugations per inch and 0.008 inch wall thickness should be considered. After the roll of corrugated ceramics is formed, it is mounted inside a 1/8 inch thick aluminum type using aluminum-to-alumina cement. The electrode-insulator assembly is cemented inside the corrugated ceramic roll and the end caps are put in place.

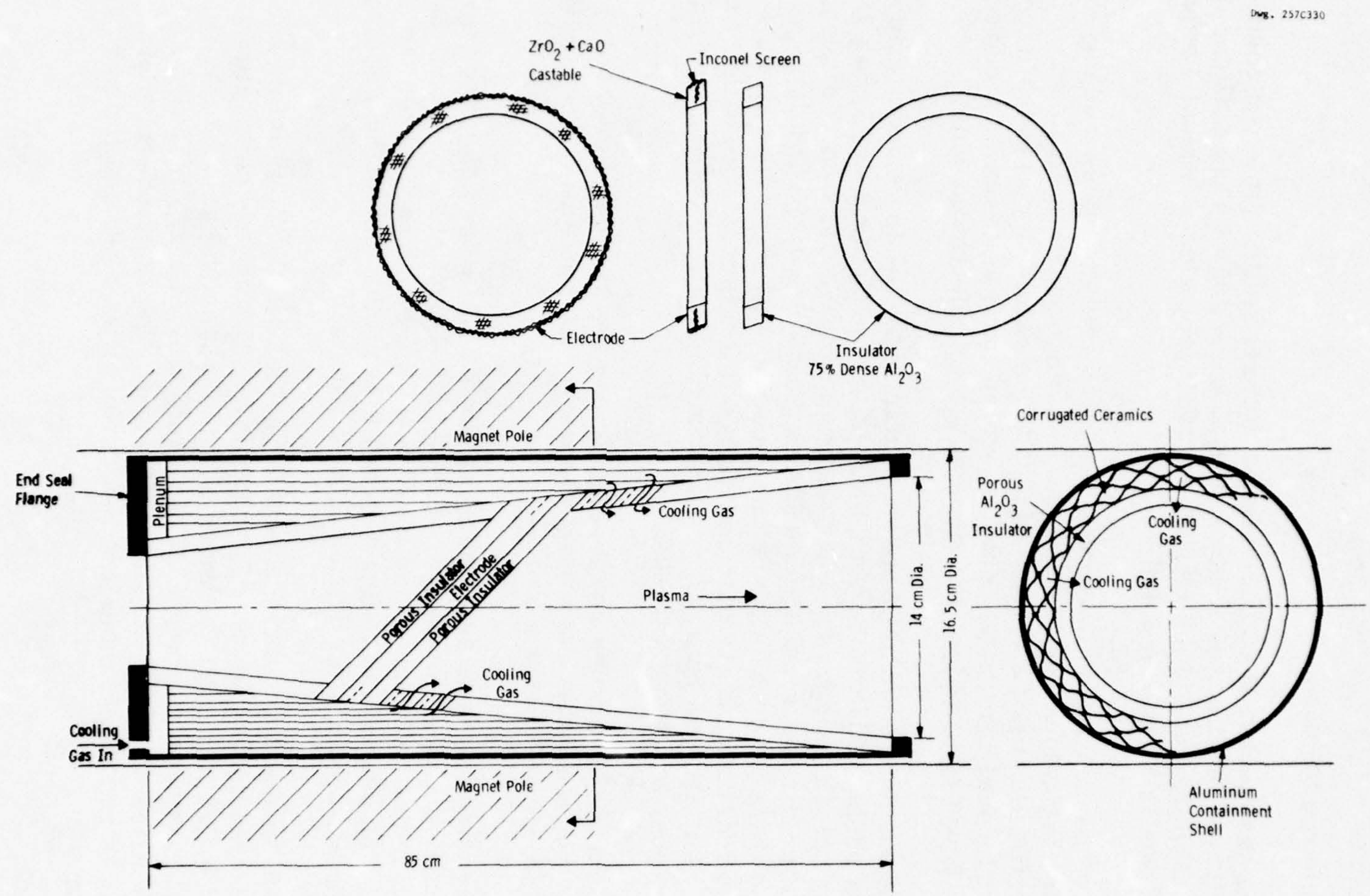


Figure V-1 - Gas-cooled MHD generator.

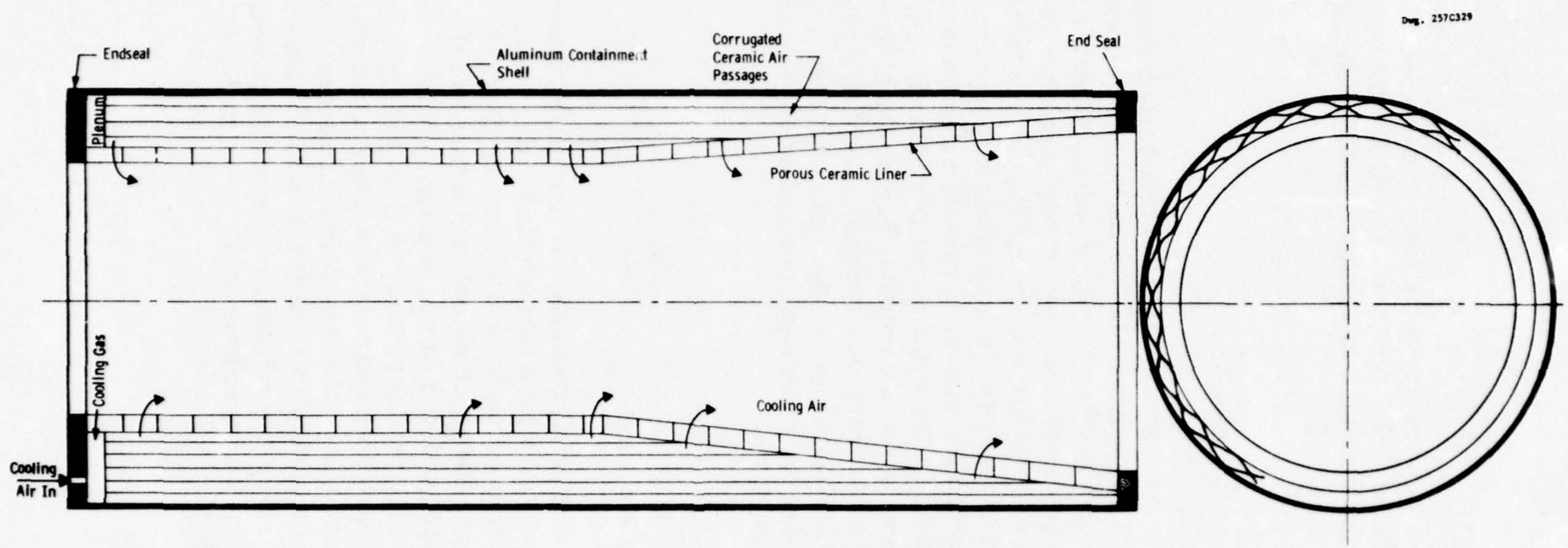


Figure V-2 - Gas-cooled MHD diffuser.

The estimated weight of an 85 cm long gas-cooled MHD generator channel is given in Table V-1. A gas-cooled diffuser has a corresponding weight savings over the conventional water-cooled diffuser.

D. High Heat Release Combustor

Westinghouse has for years designed and built combustion systems for gas turbines and MHD generators. An example of a high heat release swirl combustor is shown in Figure V-3. It was operated on liquid fuel, propane, or an ethylene oxygen mixture in test service for hundreds of hours. Heat release was approximately 1,000,000 Btu/hour or 40,000,000 Btu/ft^3/hour. A swirl burner of this sort produces very intense combustion and although water cooled as shown, achieves some additional protection particularly in the upstream end from a cooling blanket of the oxidant added tangentially in the primary zone. Ignition was accomplished either with a spark plug, a squib, or a continuously burning torch for quick light off. Many models of this combustor have been built and one eight inches in diameter is presently powering an experimental MHD generator burning benzene at our Waltz Mill site.

E. Channel Design Programs

The analysis of the MHD channel was performed using a series of computer programs developed by Westinghouse. The basis of the calculations is a Westinghouse proprietary computer program which calculates equilibrium composition, thermochemical properties and the electrical properties of the seeded products of combustion. This program requires the fuel and oxidant mole fractions, and the heat of formation of the compounds. A simple auxiliary program was used to convert toluene, seed, and oxidant compositions (given as weight percentages) into the desired form. It was necessary to modify the program somewhat to handle pure O_2 as an oxidant since the original intent of the program was for use in the design of commercial, air-blown MHD generators.

TABLE V-1

Weight Estimate for 85 cm Channel

Component	Weight, kg
Aluminum Containment Shell	3.59
Corrugated Ceramic	5.36
Porous Alumina Insulators	1.27
ZrO_2 Electrodes	2.50
Inconel Screen	0.25
End Seals	2.5
Total	15.47

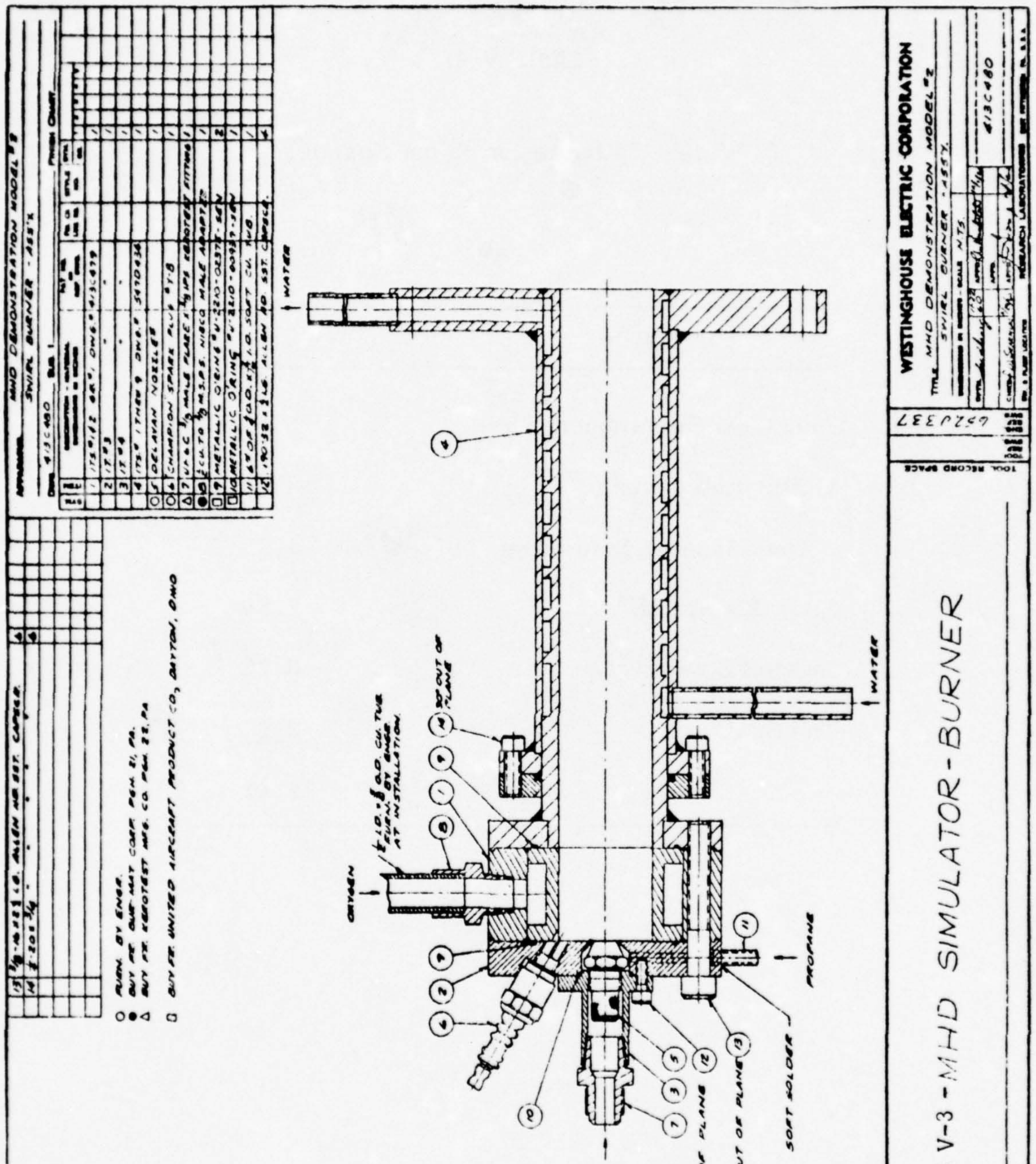


FIG V-3 - MHD SIMULATOR-BURNER

The program produced arrays of properties (over ranges of pressures from 1-8 atm and temperatures from 2500-3075°K) for the products of combustion of toluene (C_7H_8) and oxygen with 1.5% (by weight) Cr_2CO_3 or seed. These data are manipulated by a short program which sets up data files for use by the channel design program.

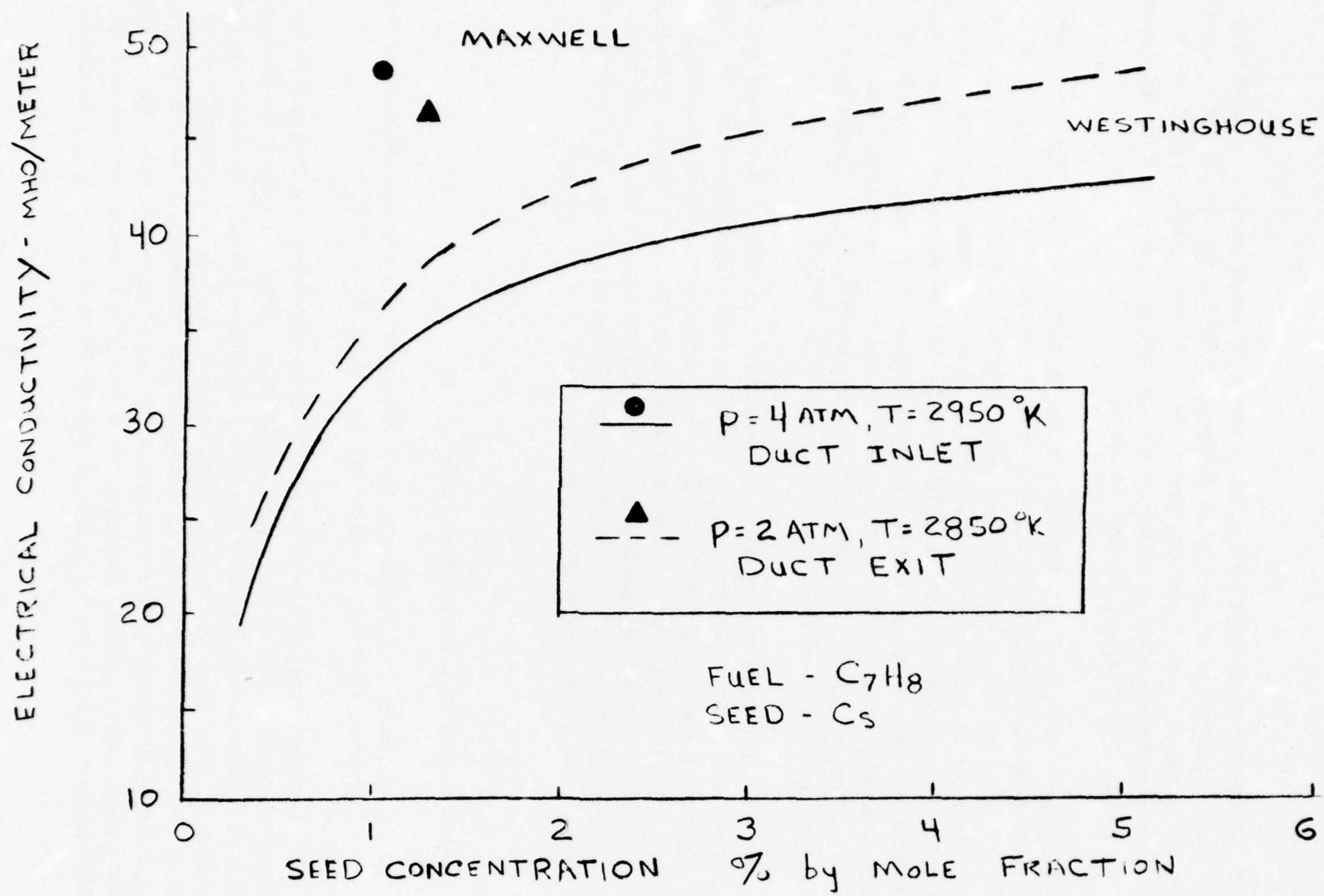
The latter program was written for the analysis of MHD power cycles with a steam bottoming plant. For the present purpose, extensive modification of the program was required to treat the MHD channel as an isolated unit, as well as to handle the high velocities under consideration. This calculation is a finite element solution of the MHD generator performance. Using data generated by the basic program, the duct program calculates the duct geometry required for a specified small pressure step. For the small step, the properties of the fluid are assumed to be constant and uniform over the cross section.

The duct program begins with a specified combustion pressure and temperature and calculates the static pressure and temperature at the inlet to the channel for an inlet velocity U_o. The calculation ends when the pressure in the channel approaches a lower limit (set by ambient condition). The calculation is initially performed using an estimated mass flow rate and subsequently an iterative computation refines the guessed flow rate to that required for a specified MHD power output.

F. Discussions of Computer Results

1. Comparison of Predicted Gas Transport Properties (Based on Data Provided from Status Briefing 21, November 1975)

Several computer runs were made to generate the thermodynamic and transport properties of the combustion gas. This was done for both a liquid fuel (toluene - C_7H_8) and a solid propellant (Westinghouse assumed formulation). The data generated for a 1%, 3%, and 10% Cs seed weight fraction. The conductivity data is compared to the Maxwell Laboratories, Inc. values in Figure V-4 , for two pressures and temperatures. These conditions would approximately correspond to the MHD channel inlet and exit. The Westinghouse data predicts lower values than that listed by Maxwell.



ELECTRICAL CONDUCTIVITY - MHO/METER
50
40
30
20
10
0
1
2
3
4
5
6
MAXWELL
WESTINGHOUSE
P = 4 ATM, T = 2950°K
DUCT INLET
P = 2 ATM, T = 2850°K
DUCT EXIT
FUEL - C7H8
SEED - Cs
SEED CONCENTRATION % by MOLE FRACTION

FIGURE V-4

This difference is approximately 30% at the higher pressure (4 atm). Note also, that the combined pressure and temperature effect on conductivity for the two data sets are reversed. To achieve comparable conductivity values based on the Westinghouse models would require Maxwell to increase their seeding from about 3% (by weight) to over 10% (by weight). It should be noted that although differences in conductivity values are indicated, the other property values such as gas density and gas molecular weight were very comparable at these conditions.

2. Channel Size Comparison (Based on Data Provided From Final Briefing January 12, 1976)

In order to make a meaningful verification of the Maxwell channel design, there are a number of quantities which must be specified as input to the Westinghouse channel design program. Although several of the more important physical parameters were available, a complete description of the channel was lacking. Therefore, in order to completely characterize the channel, certain assumptions had to be made. The data available from Maxwell (the presentation handout of 1/76) are summarized as follows:

Inlet Conditions

Stagnation Pressure = 30 atm

Stagnation Temperature = 3700°K

Stagnation Fuel = JP-5

Stagnation Oxidant = LOX

Mach Number = 1.85

Peak Magnetic Field = 4T

Midpoint Conditions

Static Pressure = 2 atm

Static Temperature = 2900°K

Velocity = 1800 m/s

Conductivity = 39 mho/m

The channel design program uses the combustor stagnation pressure and temperature, the air equivalence ratio, and the inlet velocity. The pressure and temperature were given above, and the inlet velocity was calculated to be 1870 m/sec. using the acoustic velocity at 5 atm, and $3100^{o}K$, and the specified Mach number. The air equivalence was assumed to be equal to 1.0.

There was no indication of the amount of seed used for the Maxwell design. Some iteration on the conductivity of the gases showed that a concentration of 1.5% Cs_2CO_3 by weight gave comparable conductivity at the temperature specified.

The magnet used by Maxwell had a peak field of 4.0T in the duct, with an unspecified taper in the direction of flow resulting in a field of 2.75T at the duct exit. The taper assumed here was 0.46T/atm.

In order to complete the characterization of the generator (which the program assumes is a segmented Faraday generator) a loading coefficient (K), is required as well as some velocity profile coefficient (C). The loading coefficient was initialized at 0.82 and decreased with decreasing pressure according to the relationship

$$\frac{dK}{dp} = 0.05 - 0.0025 \times PMHD \times 10^{-8}$$

where PMHD is the power output of the MHD generator.

Since no data on exit velocities or diffuser efficiency were given, the diffuser was eliminated from the program.

Table V-2 summarizes the important points of comparison.

It may be noted that the comparison is quite good on all points. The most important parameters, i.e., mass flow and active duct length are approximately 10% lower for the Westinghouse design, but this discrepancy is probably within the bounds of error admitted into the calculation by the need for so many assumptions. The duct length, in particular, could be increased if a diffuser were used. Since no data on exit conditions or the

Table V-2

Operating Parameters

	Westinghouse	Maxwell
Fuel	C_7H_8	JP-5
Oxidant	LOX	LOX
Peak B field	4 T	4 T
Inlet stagnation pressure	30 atm	30 atm
Inlet stagnation temperature	3700°K	3700°K
Inlet Mach No.	1.85	1.85
At midpoint in channel		
Static temperature	3065°K	2900°K
Static pressure	2.52 atm	2 atm
Velocity	1799 m/s	1800 m/s
Hall parameter	1.02	1.0
Conductivity	43.0 mho/m	39 mho/m
Results		
Power out	25 MW	25 MW
Mass flow	23.5 kg/s	25 kg/s
Ratio of Outlet Dimension to Inlet Dimension	2.11	2.05
Active duct length	0.90 m	1.0 m
Outlet B field	2.66 T	2.75 T
Inlet dimension	15.6 cm	18 cm

diffuser itself were supplied, it was decided to eliminate the diffuser from the calculation, and stop the calculation when the pressure in the duct reached the ambient conditions. Generator design details are given in the attached computer output, Table V-3.

Given the limited data available for evaluation of the Maxwell design, the comparison of the Maxwell configuration and the configuration computed by Westinghouse computer programs shows a reasonable degree of similarity. A more exhaustive and definitive confirmation of the Maxwell design would require more data.

G. Superconducting Magnet

The proposed magnet design was checked and comments follow. The principle characteristics are summarized in the attached table from that presentation (Table V-4).

The solution for the flux densities is a three-dimensional magnetic field problem. However, the solution can be approximated by using a two-dimensional formula for the field* using the magnet cross section at the inlet and at the outlet. Assuming that the winding build would be decreased by the ratio of the diameters, the results were a flux density of 4.08T at the inlet, and 2.4T at the outlet. This also assumes a perfectly sinusoidally varying current density around the periphery of the magnet, which might be somewhat difficult to achieve in a practical winding.

This calculation neglects any provision for magnetic shielding of the magnet. If an iron shield is used, the flux densities would be greater; if an image coil shield is used, the flux densities would be decreased. Thus, we must assume an iron shield will be provided since the non-ideal winding distribution will tend to reduce the flux densities calculated, and the outlet flux density was already lower than that stated in the table. If this is the case, the inlet and outlet flux densities (4T and 2.75T) are reasonable.

---

* J. L. Kirtley, Jr., "Basic Formulas for Air Core Synchronous Machines", IEEE Conference Paper 71CP155-PWR.

Table V-3

MHD Generator Design

GENERATOR DESIGN

POINT	LENGTH	D/D4	P	T	SIGMA	H	RHO	U	MU	S	N	MU*B	K	B
400	.000	1.000	4.518	3119.	33.687	•••••••••	.5156	1869.0	.1785	10015.9	.3938	.7142	.620	4.00
401	.056	1.056	4.268	3158.	39.965	•••••••••	.4733	1826.3	.1900	10152.4	.5202	.7600	.638	4.00
402	.108	1.087	4.018	3147.	40.282	•••••••••	.4474	1822.8	.2003	10160.7	.5209	.8012	.624	4.00
403	.161	1.121	3.768	3135.	40.677	•••••••••	.4214	1819.2	.2130	10170.0	.5157	.8252	.611	3.87
404	.215	1.159	3.518	3122.	41.099	•••••••••	.3953	1815.5	.2273	10179.9	.5109	.8533	.598	3.75
405	.272	1.201	3.268	3109.	41.534	•••••••••	.3689	1811.8	.2430	10190.5	.5065	.8849	.586	3.64
406	.330	1.248	3.018	3096.	41.970	•••••••••	.3424	1808.0	.2603	10201.7	.5025	.9195	.574	3.53
407	.391	1.301	2.768	3080.	42.549	•••••••••	.3159	1803.6	.2838	10214.5	.4980	.9709	.562	3.42
408	.454	1.361	2.518	3064.	43.165	•••••••••	.2892	1798.9	.3111	10228.6	.4932	1.0296	.550	3.31
409	.520	1.432	2.268	3046.	43.788	•••••••••	.2622	1793.8	.3420	10244.1	.4886	1.0944	.538	3.20
410	.589	1.515	2.018	3028.	44.403	•••••••••	.2349	1788.3	.3765	10260.8	.4843	1.1654	.527	3.10
411	.661	1.614	1.768	3004.	45.426	•••••••••	.2077	1781.3	.4373	10282.8	.4783	1.3015	.514	2.98
412	.736	1.737	1.518	2978.	46.546	•••••••••	.1801	1773.3	.5131	10307.9	.4726	1.4683	.502	2.86
413	.815	1.895	1.268	2950.	47.657	•••••••••	.1521	1764.7	.6027	10335.9	.4675	1.6607	.491	2.76
S	.897	2.106	1.021	2921.	48.662	•••••••••	.1238	1755.4	.7048	10366.4	.4635	1.8770	.481	2.66

SHORT BURST GENERATOR DESIGN AIR FORCE
TOLUENE FUEL 1.5% BY WEIGHT

PHI = 1.00 PMHD = 2.50000+07 TCOMB = 3700.0 PCOMB = 30.000 UU = 1869.00
MG 1.381286+01
MG 2.369252+01
MG 2.349718+01
MG 2.350827+01

Table V-4

TABLE OF SUPERCONDUCTING MAGNET CHARACTERISTICS

Dimensions	
Dewar	
Inlet Warm Bore Dia. (m)	0.29
Outlet Warm Bore Dia. (m)	0.53
Inlet Outside Dia. (m)	0.74
Outlet Outside Dia. (m)	1.10
Length Overall (m)	2.20
Magnet	
Inner Dia. at Inlet (m)	0.35
Inner Dia. at Outlet (m)	0.59
Winding Build (m)	0.034
Length Between End Turns (m)	1.20
Length Overall (m)	1.57
Electrical Characteristics	
Field at Inlet (T)	4.0
Field at Outlet (T)	2.75
Length of Field (m)	1.05
Peak Field (T)	5.6
Transverse Variation (%) - Across MHD Duct	5.0
Stored Energy (10^6 J)	2.50
Inductance (H)	1.24
Current (A)	2,000
Overall Current Density ($10^8 A/m^2$)	1.5

Lacking means of solving three-dimensional field problems, one cannot evaluate the peak field (5.6T) and the transverse variation (5%). However, from experience in designing superconducting coils for machinery applications, these figures seem reasonable.

A crude calculation of inductance indicates that the given figure (1.24H) may be a bit low. However, the methods of calculation used are not sufficiently accurate to make a firm statement.

In general, we would conclude that this design seems very reasonable providing that an iron shield is used. Otherwise, these numbers are optimistic.

H. Summary

The overall purpose of this work was to review the technical basis on which Maxwell premised their short-burst MHD channel and magnet analysis and designs. This work is based on the data and information that was presented at two technical briefings. There were

- High Power Study Status Briefing
  November 21, 1975

- High Power Study Status Briefing
  January 12, 1976

The Maxwell study encompassed both liquid and solid (solid propellant) fuels. The overall results of this Westinghouse review for liquid fuels would indicate that the Maxwell design appears consistent with regard to channel overall size, power density and operating parameters. The major weakness of their composite channel-diffuser design would be its inflexability as an experimental test vehicle. This could lead to relatively expensive and long channel testing program.

A comparison of the Westinghouse and Maxwell specific gas property value data based on the earlier technical briefing showed an inconsistency in the values obtained for gas conductivity. The significance of this difference however was not fully explored since the actual seeding fraction utilized by Maxwell was uncertain with regard to their design presented in their final briefing.

In regards to the magnet and power conditioning system it was noted that:

(1) The Maxwell weights and volumes for the power conditioning equipment may be on the low side but it is difficult to tell since actual performance specifications were not available.

(2) The magnet design is reasonable if an iron shield is used, otherwise the numbers are optimistic.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

Specific weights of 0.03 to 0.1 lbs per kVA at 99 percent efficiency are typical of the superconducting machines expected for these applications, and that is for continuous output anytime it is needed. The old myths of restrictive amounts of auxiliary equipment being required for the superconducting system were dispelled in the study as the facts show they constitute only about a 50 percent addition to the basic generator weight. The total superconducting generator system weights are typically one-half to one-fourth of comparable conventional generator system weights, and at high voltage, the difference becomes even greater, e.g., one-tenth. With continued development of superconducting generators, the weights will likely be halved from their present low values. As a result, it is clearly recommended that continued development be carried out on superconducting generators. Whether comparable development of conventional generators should be carried out is doubtful. There are certainly no performance advantages, and if one seeks a lower risk advantage, he or she could easily be fooled. As indicated in the text, the so-called conventional designs certainly do not connote low risk unless one is willing to sacrifice significant system weight, system complexity due to paralleling, etc.

Comparison of purely thermal inertia machines and a fluid cooled system tend to favor the latter. From the weight standpoint alone, the thermal inertia machines did not appear favorable except for run times of less than approximately one-third minute. Fluid cooling provides more versatility in run times plus increasing weight savings as the operating time increases.

Application of the Gramme ring winding to the superconducting generator represents a new and very significant innovation, even though individually both represent rather old ideas. Because of the unlimited and high voltage choices it opens up to the designer, its development should be pursued in earnest, starting with fundamental design technique verification and concluding with the application of a full rated winding to a superconducting machine, e.g., the 10 MW model being developed on USAF Contract F33615-71-C-1591 (second generation of course). Having an unlimited ac voltage choice should also simplify the power conditioning task. This could prove to be a very significant benefit in the future should the potential problems of that task (especially DC to DC conversion) become a reality.

In conjunction with the development of the Gramme ring, application development of the high voltage stator insulations and bore seal should also be started. The key word here is "application" because most of the basic high voltage insulation technology that is needed exists today in large commercial transformers, distribution systems, etc.; it only needs to be specifically applied and up-rated for the need at hand.

The key to the low helium consumption of these larger machines is the warm damper shield. Development of the basics for such shields are being carried out now on the large central power station development programs for two pole rotors. Although the basic development problems are less severe on four and six pole rotors, application development should be carried out as soon as possible on warm damper shield design approaches for the designs proposed herein. Again, it would be apropos to include such in the 10 MW model (second generation again) of F33615-71-C-1591.

Although the startup times envisioned for the superconducting generator are less than the taxi/takeoff times envisioned for the aircraft, it is nevertheless desirable that development be continued to find ways of achieving the desired one second startup. This can only be done through hardware testing and analysis; the analytical means to tackle that problem from a purely computational standpoint do not exist. Such a development would also likely lead to an even more attractive cyrogenic standby or "ready" scenerio, possibly even to the extent of obviating the need for the over-running clutch between the turbine and generator.

Relative to the proposed over-running clutch, the basic technology for such exists today, e.g., on the HLH helicopter program. Nevertheless, application development should be carried out on the specific designs needed herein.

The separate testing of such large multimegawatt generators can be a real problem because the available driving sources and output absorption devices are <u>very</u> limited. It is therefore recommended that in the future, two machines be built and that they be tested in a feed-back arrangement wherein one acts as a motor driving the other as a generator. The motor power is taken from both the driven generator and a make-up power source. This type of synchronous machine testing has been done routinely for years and into the tens of thousands of horsepower. It has an added nice feature of being fail safe. Because of the high efficiency of the superconducting generators, a pair of 25 MW machines would only require an 800 horsepower make-up motor; comparable conventional generators would require 4000 HP.

Also application of wireless data coupling to the rotor(s) should be utilized for future tests, eliminating the need for thermometer slip rings, thereby greatly simplifying the driving source shafting arrangements.

Finally, regardless of the eventual choice of power source (superconducting, conventional, MHD, etc.) fault control and protection schemes will have to be worked out and developed. Switches, valves and fields (rotating or stationary) may not be able to shut down fast enough (in and from their natural operational modes) to prevent the power source from damaging the fault zone (wherever it is) beyond repair. For example, a superconducting field has an inherent self protection feature of quenching in case of an output fault, except that it may take one hundred milliseconds to complete the quench. The output of a power source of multimegawatt capacity into a fault for even a 100 millisecond can be disastrous.

APPENDIX A

RECTIFICATION CONSIDERATIONS

R. J. SPREADBURY

1. INTRODUCTION

A requirement has appeared for a rectifier installation, suitable for 400 Hz operation, and at relatively high power levels. The effect of the rectifier load on the machine terminals is required, considering waveform distortion, harmonic currents and transient overvoltages. The application and load is not well specified but the following data has been assembled and used for preliminary assessment.

2. POWER RATING

Covers the range of 10 MW to 50 MW. These figures are based on the actual load drawn during the operating phase. It is not the average power.

3. DC OUTPUT VOLTAGE

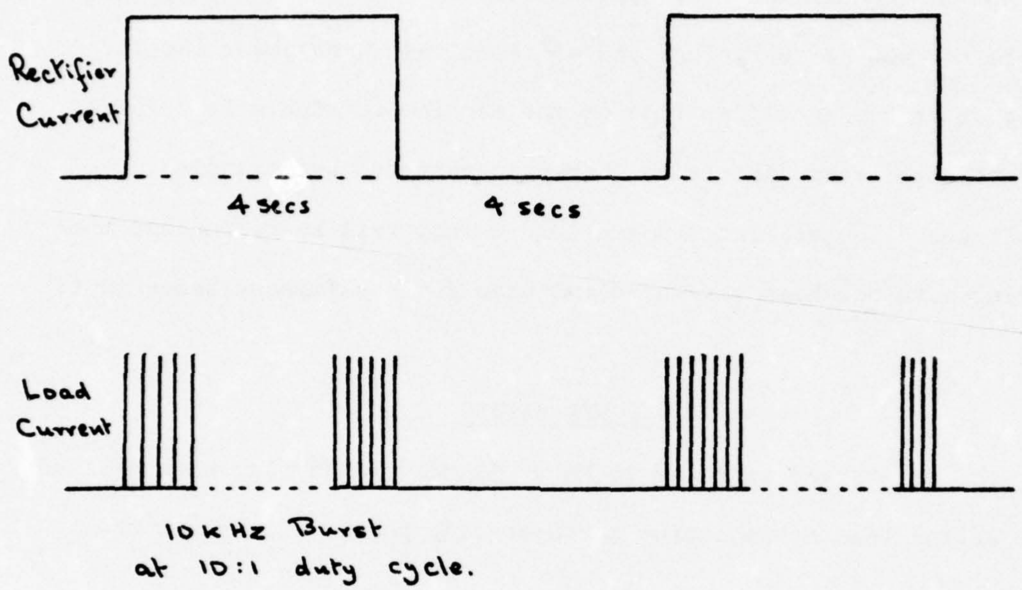
20 kV - 200 kV.

4. LOAD CHARACTERISTICS

There is a 10 kHz pulsing load (with a probable duty cycle of 10:1), fed from an energy store capacitor, which, in turn, is fed from the rectifier.

The capacitor is assumed to be isolated from the rectifier installation by some form of inductive filter so that the current drawn from the rectifier is essentially constant during the operating phase.

The burst of 10 kHz load pulses are interspersed with quiescent periods with a worst case duty cycle of 4 secs on and 4 secs off. The rectifier load profile is thus as sketched below.



5. AC SOURCE

Two possibilities have been raised on an ac power source. In both cases, the rectifier load constitutes virtually the entire load on the generator. No designs yet exist but the probable range of applicable characteristics is as indicated. They are:

5.1 Superconducting Machine

Per Unit Synchronous Reactance: 0.15 - 0.3

5.2 Conventional Machine

Per Unit Synchronous Reactance: 1.16 - 1.8

Discussions with machine designers at Lima and Westinghouse Research indicates that subtransient reactance X''_d and X''_q are approximately equal due to the fact that there is no iron in the rotor. A present theoretical design for a 5 MVA superconducting machine has the following characteristics:

X_s = 0.311 (Synch. Reactance)

X'_d = 0.268 (Transient Reactance)

X''_d = 0.2 (Subtransient Reactance)

6. RECTIFYING CIRCUIT

It is assumed that semiconductor elements will be used in this application. The voltage (though high at the upper end) are not completely out of court and the power levels are very definitely obtainable.

Preliminary request direction was towards a simple uncontrolled rectifier installation with voltage control for the load (if necessary) via the machine field.

However, with the short duty cycle, the response of a field control becomes critical. Discussion with Lima indicates that a conventional machine can build up from zero to full field (with about 30% forcing) in around 150 mS and would expect to be able to handle a no load - full load transient in around 15 mS. These time constants are short and comparable performance from a superconducting machine may be doubtful (due to field normalization).

If a reduced performance is inadmissible, consideration may have to be given to a controlled rectifier installation. This alternative is considered later.

7. GENERAL THOUGHTS ON CONNECTION

For minimum size and weight of the dc filtering elements, a number of phases is required. However, at the voltages we are considering, the number of devices in series required per leg and the concurrent cooling and mounting of them calls for a minimum number of rectifying legs.

Under the circumstances, it does appear that the full wave three phase bridge connection offers a reasonable compromise.

Since, presumably, minimization of the machine winding voltage is required, a wye connected machine is an obvious first choice.

For the sake of completeness, some alternative connections are sketched in Figure 1. Three, at least, would require six windings on the machine, while the 12 pulse circuit would also require an interphase transformer (probably inadmissible from the weight minimization point of view).

The "voltage doubling" circuit, Figure 1f, is somewhat unconventional and, in addition, would require two intermediate, high voltage, high energy store capacitors. Its only advantage, as far as I can see, is that the machine winding voltages could be reduced by about 15%.

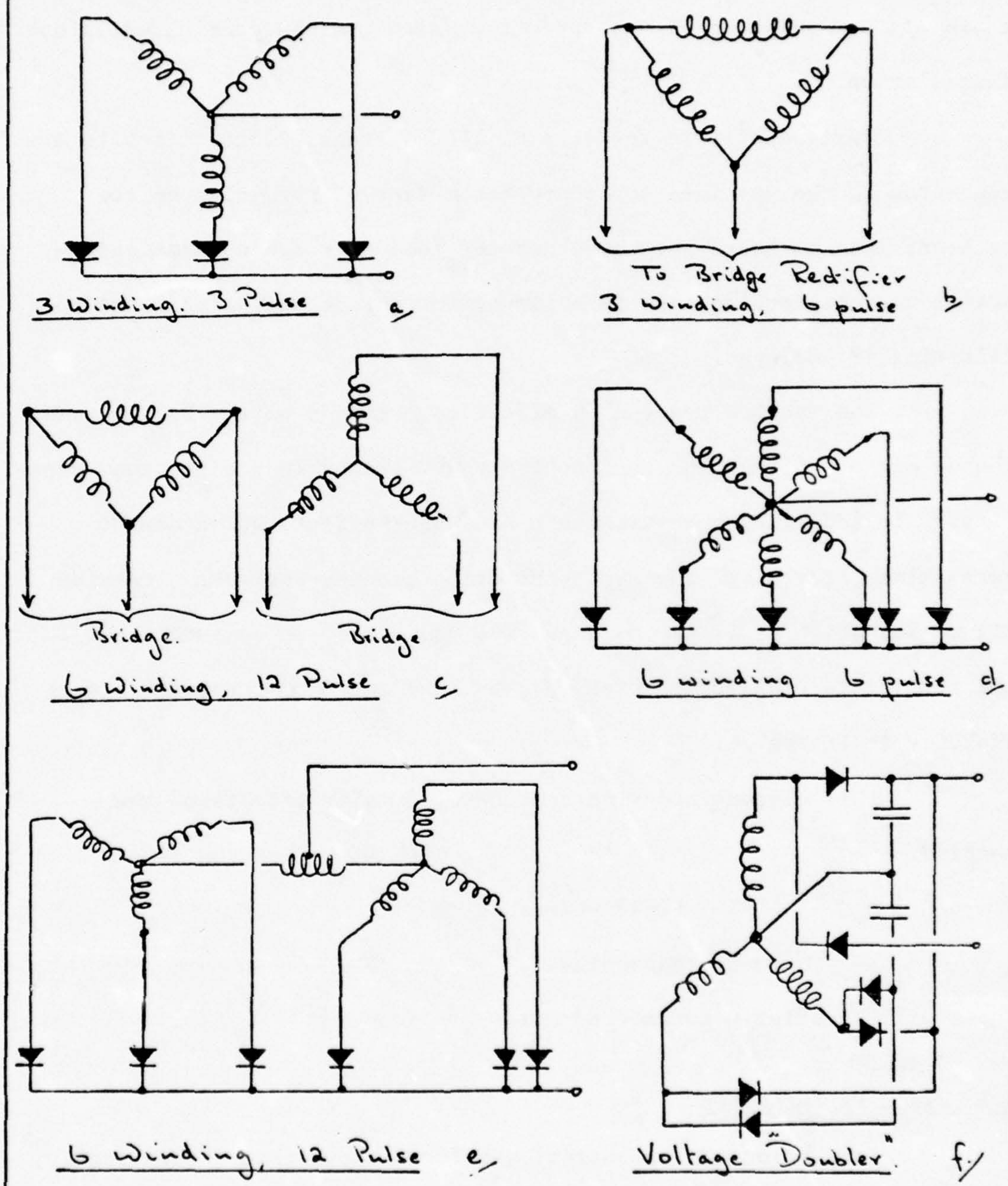

3 Winding. 3 Pulse a/
To Bridge Rectifier
3 Winding, 6 pulse b/
Bridge.
Bridge
6 Winding, 12 Pulse c/
6 winding 6 pulse d/
6 Winding, 12 Pulse e/
Voltage "Doubler". f/

Fig. 1.

8. THE MACHINE ON RECTIFIER LOAD

Complete machine loading by a rectifier bridge is common practice (ac exciters, HVDC transmission systems, etc.), however, there are some aspects of such practice which must be considered before installation.

Particularly in the case of HVDC systems, filter circuits are connected in the ac lines to reduce the effect of harmonics on the machine; line currents and the generator load approaches normal sinusoidal current loading. It is assumed, for this application, that no filtering is employed.

The machine reactances affect commutation of the bridge arms, the dc output voltage and the machine power factor (hence its load capacity). In addition, however, there are other effects which are of particular interest to the superconducting machine designer. Consider Figure 2a, which shows the machine, wye connected, in conjunction with the rectifier. Neglecting overlap, the line and diode currents are as sketched in Figure 2b.

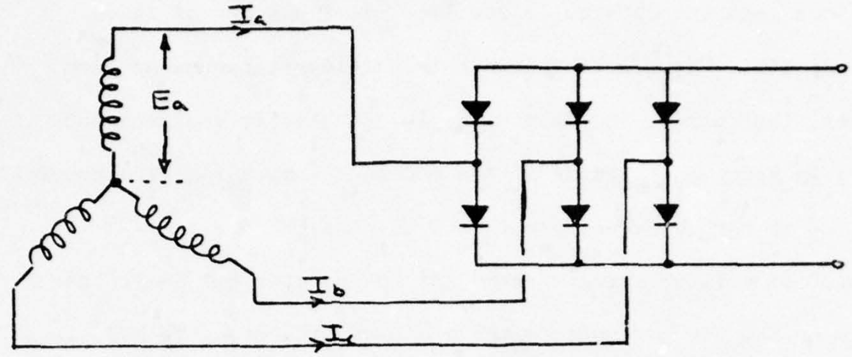
This discontinuous current has two major effects on the machine.

1. Field perturbation.
2. Harmonics.

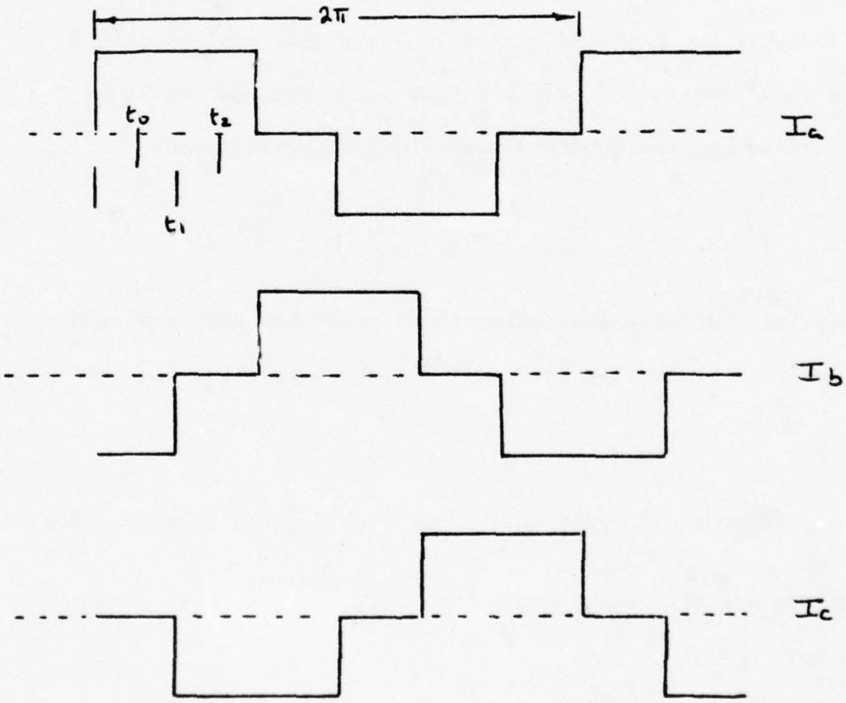
These will be briefly considered next.

8.1 Field Perturbation

Inspection of the current waveforms shows that theoretically, at least, there is always a one to one current balance, i.e., as much



Basic Machine with Rectifier Load. a



b

Line (and Diode) Currents of Bridge Rectifier

Fig. 2

current flows into the machine on one line, as flows out of it on another. However, between the current transition instances at each $\pi/3$ radians, the current in the machine is essentially constant and <u>stationary in space</u>. The rotor of the machine is spinning at a constant speed of ω so that between, say t_o and t_1, the MMF due to the rotor field will be swinging ahead of the counter MMF due to the armature. At t_1, the currents switch again and the armature MMF steps forward to t_2, thus swinging ahead of the rotor MMF. This periodic imbalance of the MMF's will give rise to a flux pulsation in the field winding and hence a ripple in the field current. The ripple amplitude is a function of the load current[3,5] and the flux perturbations may be of interest when considering the cooling losses in a superconducting machine.

8.2 Harmonics

Neglecting overlap and assuming the current waveform sketched in Figure 2b, analysis by Fourier series[4,5] gives a solution for the current of

$$i = \frac{2\sqrt{3}}{\pi} I_d \left[\cos wt - \frac{1}{5}\cos 5\,wt + \frac{1}{7}\cos 7\,wt - \frac{1}{11}\cos 11\,wt + \frac{1}{13}\cos 13\,wt \ldots\right]$$

i.e., the harmonics are all of the order $6k\pm1$ with the rms value of any term given by:

$$I_{(M)} = \frac{\sqrt{6}}{n\pi} I_d \qquad (I_d = \text{dc load current})$$

so that the fundamental current (n = 1) is given by:

$$I_{(1)} = \frac{\sqrt{6}}{\pi} I_d = 0.78\, I_d$$

which compares with the winding rms current rating of

$$I_{(M)} = \sqrt{\frac{2}{3}}\ I_d = 0.816\ I_d$$

Of particular interest is the 5th harmonic current of value

$$I_{(s)} = \frac{\sqrt{6}}{5\pi}\ I_d = 0.1632\ I_d$$

which produces a reverse (or negative) rotating field and hence torque in the machine. While the 11th, 17th and 23rd are also negative, their amplitudes are correspondingly reduced and are probably negligible.

8.3 Overlap and Commutation

The machine windings possess some reactance and resistance. During commutation from one phase to the next, the windings are essentially short circuited through the diodes and a finite time (or vector angular displacement) is required to transfer the load current. The transfer time (or "commutation" angle) is thus a function of the effective reactances in the short circuited phases and the load current.

The effective reactance during this interval is usually taken as the subtransient reactance X''_d (which is present only with machines having damper windings). For simplicity, it is generally assumed that the X''_d term is adequate and constant. However, with higher load currents and hence larger overlap times, the resultant armature current MMF, during the overlap, will have both "d" and "q" axis resolved components and hence the commutating reactance will increase. This may be the rationale for using $\frac{X''_d + X''_q}{2}$, which is advocated by some engineers.

For non-salient pole machines, a transient ~~radience~~ reactance (X'_d) value is usually available. For the purpose of this study, it is assumed that the machines will be salient pole.

With such a proviso, it would appear that a machine specifically designed for rectifier operation would have certain additional design aims, viz.:

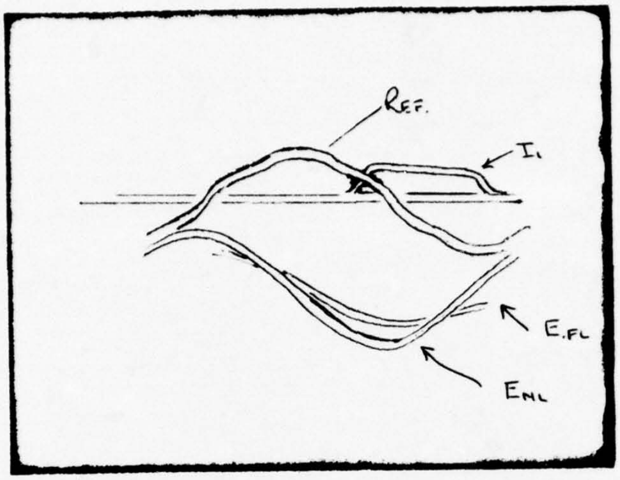
(i) Reduce the commutation angle to obtain maximum possible operating power factor.

(ii) Reduce the field and damper current perturbations to reduce the machine loss.

Certainly a reduction in L''_d and L''_q would reduce the commutation angle (or time) and would also reduce the relative effect of the field in the direct axis. Both effects will reduce the commutation disturbance on the voltage waveform. Unfortunately, the reduction of L''_d and L''_q will increase the damper current perturbation[3] and unless damper circuit resistance is lowered, damper loss will increase.

The design is thus somewhat more critical than for a conventional machine.

The effect on the terminal voltage waveform of the commutation short circuit is clearly shown in Figure 3a. This photograph was taken on a 50 kW machine during tests for another application. However, the machine was still loaded with a three phase bridge. The apparent phase shift between the no load (E_{NL}) and full load (E_{FL}) waveforms is, in fact, only the result of using a reference waveform generated by a shaft position indication (Ref) and is a measure of the load angle in the machine.



Machine Terminal Waveform Distortion on Rectified Load. Fig. 3a.

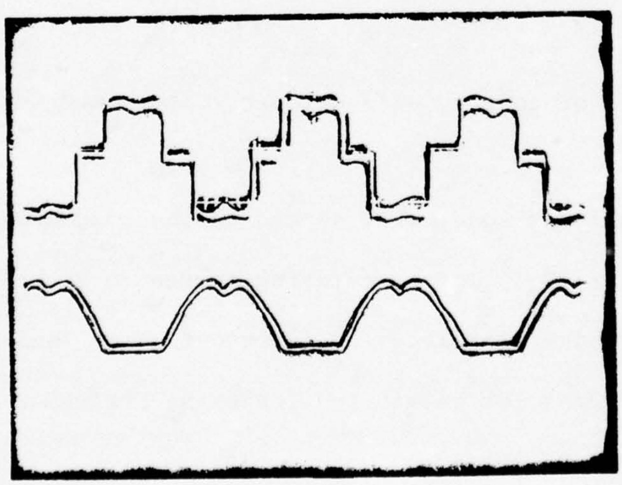


Fig. 3b.

Reverse Current "Spikes" at the end of Commutation with the Three Phase Bridge Rectifier.

The commutation "short circuit" time (or angle) is uniquely set by the commutating reactance, the dc current and the ac voltage. Appendix 2 derives a formula for Cos u (the overlap angle) which is extremely simple viz.:

$$\text{Cos } u = 1 - X_{P.U.} \frac{I_L}{I_{FL}}$$

where $X_{P.U.}$ = per unit reactance

I_L = rms load current

I_{FL} = full load rms current

9. THE BRIDGE RECTIFIER

Design formulae for the three phase bridge rectifier is commonly available (see Appendix 1) and, when applied to the power/voltage requirements, results in the matrix of voltages and currents shown in Table 1.

These values are, of course, open circuit voltage and full load currents.

The actual voltage, or load, will depend on the load current and the commutating reactance X_c. The commutating reactance X_c being the sum of subtransient machine reactance and interconnecting lead reactances. For varying per unit reactances, we obtain the following percentage drop in dc output voltage at full load:

Per Unit Reactance	0.1	0.14	0.18	0.22
% Drop in dc Voltage	5	7	9	11

with proportionally less at less than full load current.

Power Requirements

Power MW.	Voltage Levels. (V_{do}) kV. 20	40	60	80	100	120	140	160	180	200
10	500	250	166.6	125	100	83.3	71.4	62.5	55.5	50
	166.6	83.3	55.53	41.66	33.33	27.76	23.8	20.8	18.5	16.6
	R620	S9	S9	S9	S8	S8	S8	S8	S6	S6
20	1000	500	333.2	250	200	166.6	142.8	125	111	100
	333.2	166.4	110.8	83.2	66.4	55.2	47.6	41.6	37	33.3
	R620	R620	R620	S9	S9	S9	S9	S9	S8	S8
30	1500	750	500	375	300	250	214.2	187.5	166.5	150
	500	250	166.6	125	100	83.3	71.9	62.5	55.5	50
	R620	R620	R620	R620	S9	S9	S9	S9	S9	S9
40	2000	1000	666.4	500	400	333.2	285.6	250	222	200
	666.4	333.2	222	166.6	133.3	111	95.2	83.3	74	66.6
	R720	R620	R620	R620	R620	R620	S9	S9	S9	S9
50	2500	1250	833	625	500	416.5	357	312.4	277.5	250
	833	416.5	277.6	208.3	166.3	138.8	119	104	92.5	83.3
	R720	R720	R620	R620	R620	R620	R620	S9	S9	S9.

← I_{do}
← I per device (Average)
← Possible device Type.

E_a(kV)	8.547	17.1	25.64	34.188	42.735	51.282	59.829	68.376	76.923	85.47
E_{LL}	14.8	29.6	44.4	19.738	24.673	88.82	103.626	118.43	133.23	165.358

Required a.c. Machine Voltages

Table 1.

It will be noticed that the winding and interconnection resistance has been neglected. This is a reasonable assumption for "normal" applications. In general, it is found that if the resistance is at least an order lower than the reactance, it can be neglected, both from the rectification and operation point of view[10].

This, however, raises an interesting point. It is assumed that the rectifier will be operating normally in the so called "1st mode" of operation, i.e., the overlap angle is less than $\frac{\pi}{3}$ (60°) and load current is transferred over one pair of rectifiers at a time. With the pulsing nature of the load there may well be an incentive to uprate the machine during the operating interval so as to reduce the overall size and weight. Under these circumstances, the operation could run into the so called "2nd mode" of operation when a two phase short circuit is switched around the machine, i.e., three rectifiers are conducting at all times.

This possible mode of operation is particularly important if controlled rectifiers are ultimately required to meet the regulation response times. In this mode (2) it is possible (at certain loads and control angles) for the controlled rectifier to become uncontrolled.

10. RECTIFIER DEVICE SELECTION

As is well known, Westinghouse Semiconductor Division manufacture a wide range of rectifier devices and also provide a range of high voltage rectifier stacks. In the latter, devices are assembled into a series chain incorporating voltage sharing passive components.

With the help of Westinghouse Youngwood, a provisional allocation of standard modules and individual rectifiers have been made to the range shown in Table 1. These are shown in Table 1 in the third row of each group.

It is a fact of life that semiconductor devices do not exhibit "perfect" characteristics, i.e., it is possible for a rectifier to pass current (for a short time) in the reverse direction immediately after passing forward current. The magnitude of this current pulse and its time are inversely related and effectively represent a "current x time" quantity which is unique to the device and is called the Q_{rr}. As might be expected, Q_{rr} is not a constant but is sometimes used (for want of an alternative) as a comparative parameter for a device.

10.1 Device Snap-Off and System Overvoltage

When the dc current falls to zero in the outgoing phase of the rectifier, the rectifier does not block immediately. This means that a reverse current can now build up through the pair of rectifiers which have just finished transferring the load current. The effect is sketched in Appendix 3, and can be clearly seen at the end of the current pulse in Figure 3b. This current will, of course, be limited only by the commutating reactance and the voltage which is available to drive this current. Obviously the longer it takes to transfer the current between phases, the higher the voltage between phases at the current zero (see Appendix 2).

The reverse current will rise to a value, I_c. and the junction will revert to the blocking condition after T_1 secs. Obviously, the device cannot block instantly but the current will "snap" off relatively quickly (as sketched). The current, I_c, which was flowing in L_{C1}, will attempt to collapse, creating an overvoltage at the anode of the diode. The magnitude of this voltage will be fixed by the peak value of I_c, the "snap off" time, the commutating inductance L_c and the effective capacitance in the circuit.

Since L_c is, to a first approximation, entirely located in the machine, this transient overvoltage will be distributed over the armature windings of the machine. The actual voltage distribution is a hyperbolic function fixed by the distributed interwinding and inter-turn capacitances and, while it is somewhat dependent on whether the star point is grounded, the distribution is such as to stress the turns near the input terminals more than the rest.

It is possible to obtain so called "fast" devices. These are specially made rectifiers which exhibit very low Q_{rr} values and as such revert to the blocking condition much earlier, thus restricting I_c and hence the overvoltage. Unfortunately, this increase in speed is accompanied by a big reduction in available reverse voltage capability (as much as 50%). We will thus need a lot more devices in series per leg. In addition, the dopant (usually gold) used to enhance the turn-off speed, also causes the device to "leak" more at high temperatures which restricts the junction operating temperature to around 150°C instead of 175°C. This loss of margin may be critical with optimally packed and cooled assemblies.

Under the circumstances, it appears that the best solution is to use conventional "high voltage" rectifiers, obtain the minimum number of devices in series, and then go from there.

10.2 Stored Charge, (Q_{rr}) and Its Variation

There is a dearth of published data on Q_{rr}, particularly on the smaller devices. However, for the R702 (Fast Diode), there is a curve showing that reverse recovery time is a function of reverse di/dt.

To judge from the curve, the device tends to a constant Q_{rr} effect with di/dt from 0-30 A/μS and a constant time from around 40 A/μS out to 200 A/μS.

Since one would not expect di/dt to be any greater than the lower limit (say 25 A/μS) for this application, an assumption that Q_{rr} is constant (for a given device) allows a simple relationship to be derived for the peak reverse current (I_c) (and sweep out time, T_1) as functions of the P.U. reactance, maximum ac current and Q_{rr}. These are described in Appendix 3 and given below, viz.:

$$I_c = \left[\frac{\sqrt{3}\ 4\ Q_{rr}\ \pi\ f\ I_{FL}\ \sin\left(\cos^{-1}\left(1-X_{PU}\right)\right)}{X_{PU}}\right]^{1/2}$$

$$T_1 = \left[\frac{X_{PU}\ Q_{rr}\ \sqrt{2}}{\sqrt{3}\ \pi\ f\ I_{FL}\ \sin\left(\cos^{-1}\left(1-X_{PU}\right)\right)}\right]^{1/2}$$

where I_c = peak reverse current

T_1 = time from first current zero to instant reverse current = I_c

I_{FL} = full load ac rms line current

X_{PU} = per unit reactance

Q_{rr} = stored charge in junction

f = ac line frequency

Discussion with Westinghouse Youngwood indicates that while no extensive batch testing is carried out, sufficient test data (on the larger R720 and R620 devices) is available to indicate the probable manufacturing spread of Q_{rr}.

However, as indicated, Q_{rr} is a function of the design voltage rating and to obtain the spread, the devices should all be of the same voltage rating. In addition, Q_{rr} varies with temperature, and while no quantitative data apparently exists (or is immediately available), estimates of Westinghouse Youngwood indicate a possible change by as much as 250% from 25°C to 150°C (junction temperature).

10.3 Stored Charge and Seriesed Devices

In addition to the voltage transient problem caused by Q_{rr}, seriesed devices raise another. Series operation of devices requires some form of resistive voltage equalization chain to ensure that each device takes its share of the full voltage.

This is adequate only for quiescent voltage blocking, however Under transient conditions when reverting to the blocking condition, that device which has the lowest Q_{rr} will turn off first. This immediately starves the remaining devices of current, and the full voltage appears across the unfortunate "fast" device. To obviate this problem, dynamic current sharing is carried out using capacitors shunted across each device. The sizing of the capacitor is a function of the expected Q_{rr} differential between slowest and fastest devices in the chain. For minimum capacitor size, this differential should be small.

Preliminary information from Westinghouse Youngwood indicates that, for applications such as this, they would be willing to categorize devices into "families",where O_{rr} would be matched within some reasonable value. Initial categorization for the R620 and R720 devices being as follows:

R620 (1400 V Material)

Possible Range 150 μC to 600 μC.

Categorize into 200, 300, 400, 500, 600 μC test centers with all devices within ± 50 μC of a test center.

R720 (2000 V Material)

Possible Range 150 μC to 900 μC.

Categorize into 150, 300, 450, 600, 750, 900 μC test centers with all devices within ± 75 μC of a test center.

10.4 Series Devices and Compensation Networks

Based on the proposed category limits and assuming sharing within 10% of the device voltage, we can arrive at some suitable resistive and capacitive values for the R620 and R720 devices.

There appears to be no quantitative Q_{rr} values for the smaller D05 and D08 devices except that the present standard high voltage stacks employ 0.03 μF and 330 K elements for the D05 devices and 0.1 μF and 30 K for the D08 devices. These values are apparently based on swamping the device internal capacitance with an external capacitor value of about 100 times the size.

10.5 Overvoltage Limits

From the equations in Appendix 3, we can arrive at some reasonable estimate of the peak reverse current I_c. The magnitude of the overvoltage generated by L_c will, however, depend on how quickly the current decays, i.e., on T2 in the diagram. Estimates of T2 as a function of T1 seem to spread over the range T1/2 to T1/20. For a worst case approximation, one can assume that the entire stored energy in

the commutating inductance, L_c, is dumped into the effective shunting capacitances around the diode string.

Appendix 4 presents a more accurate calculation which considers the overvoltage as a function of I_c, L_c, the effective shunting capacitance and T_2, assuming an exponential decay for I_c.

Spot calculations made using this more complex equation, with T_2 varying over the range 1 μS to 5 μS resulted in only about 10% reduction in peak voltage. It, therefore, appears that a reasonable (and pessimistic) answer can be obtained merely by using the energy balance equation (or the second term only of the full equation).

Detailed calculations have been carried out on one device (the R720) over the range of assumed possible machine reactances at one operating voltage and power level (20 kV and 40 MW) and over the range of possible Q_{rr} (see Table 2). The overvoltages and their variation are plotted in Figure 4. While these results are pessimistic, they illustrate very clearly the penalty paid for high Q_{rr} and machine reactance.

In practice, of course, there will be considerable extra stray capacitance in the bridge and its interconnections, magnetic losses in the machine and associated hardware and the effect of the shunt voltage equalization resistors, all of which will reduce these theoretical values.

11. OVERVOLTAGE PROTECTION

As it appears certain that some overvoltages will exist, suppression will be needed if insulation levels are critical. The simplest solution is shunt capacitance on the machine terminals. This will also improve the overall load P.F.

AD-A031 620 WESTINGHOUSE ELECTRIC CORP LIMA OHIO AEROSPACE ELECT--ETC F/G 10/2
HIGH POWER STUDY SUPERCONDUCTING GENERATORS.(U)
MAR 76 A E KING, C C KOUBA, J L MCCABRIA F33615-75-C-2068

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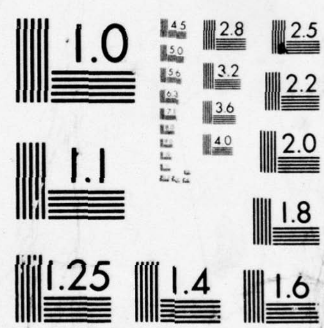


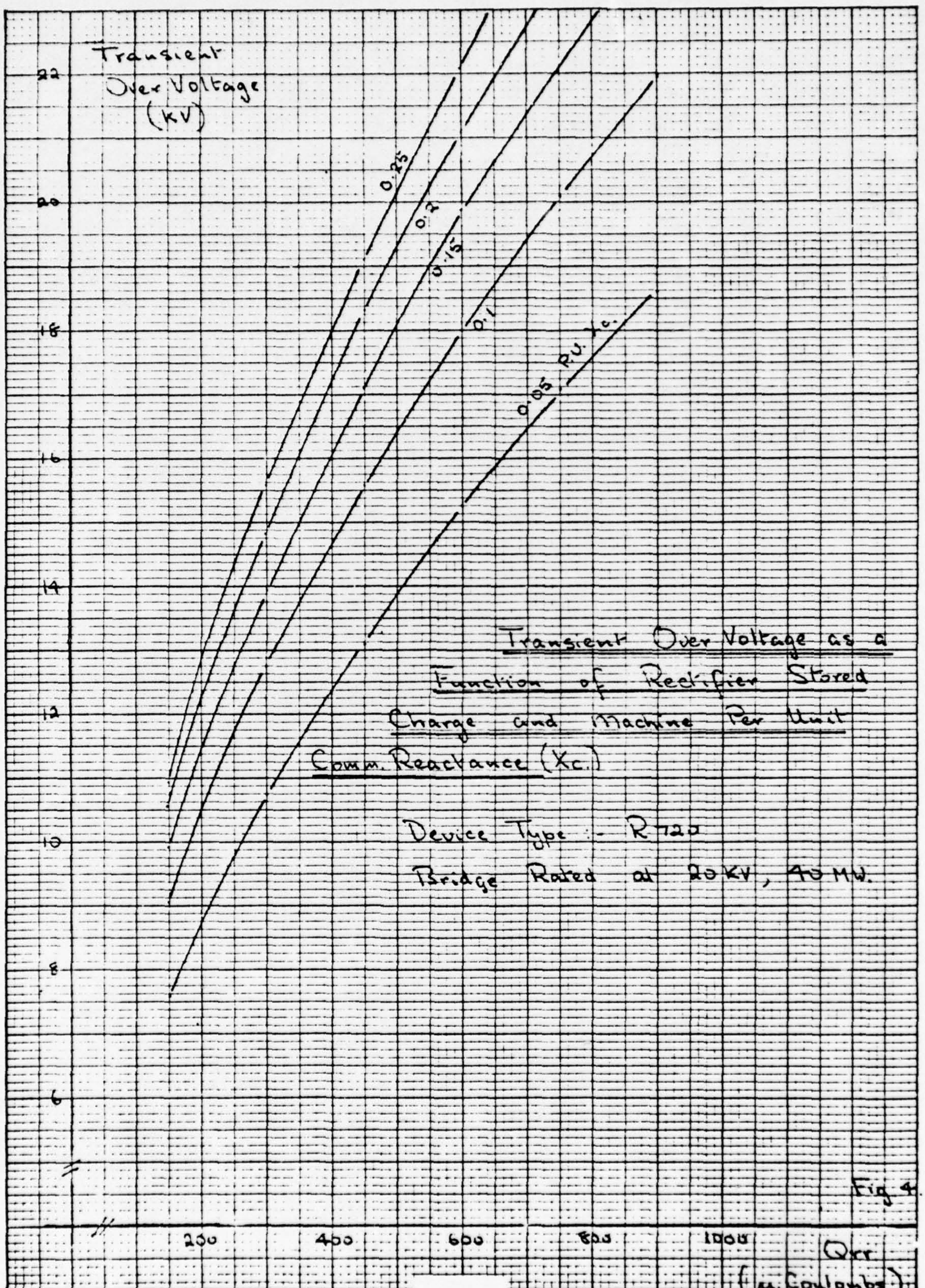
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Device :- R720, Power - 40 MW @ 20 KV d.c.
C_{eff} = 0.0234 μF, 32 devices in Series (50% safety)

$X_{P.U.}$	Q_{rr} (μC)	I_c (Amps)	T_1 (μS)	Over Voltage $= \sqrt{\frac{L}{C}} \times I_c$ (KV)	$\sqrt{\frac{L_c}{C}}$ (ohms)
0.05	150	115	3.09	7.63	66.3
	300	162	4.37	10.74	
	450	199	5.35	13.19	
	600	230	6.18	15.25	
	750	257	6.9	17.04	
	900	281	7.5	18.63	
0.1	150	96.2	3.705	9.02	93.8
	300	136	5.23	12.756	
	450	166	6.4	15.570	
	600	192	7.4	18.00	
	750	214	8.2	20.07	
	900	234	8.9	21.95	
0.15	150	86.2	4.12	9.904	114.9
	300	121.5	5.82	13.96	
	450	149.2	7.13	17.12	
	600	172.5	8.24	19.82	
	750	192.75	9.2	22.06	
	900	210.75	10	24.215	
0.2	150	79.7	4.45	10.568	132.6
	300	112	6.3	14.851	
	450	138	7.7	18.298	
	600	159	8.9	21.083	
	750	178	9.95	23.602	
	900	195	10.8	25.857	
0.25	150	74	4.75	10.952	148
	300	105	6.7	15.54	
	450	129	8.2	19.092	
	600	149	9.5	22.052	
	750	167	10.6	24.716	
	900	182	11.5	26.936	

Peak Reverse Current, Recombination Time and Over Voltage as a Function of X_{PU} and Q_{rr}.

Table 2.


Transient Over Voltage (kV)
22
20
18
16
14
12
10
8
6
0.25
0.2
0.15
0.1
0.05 P.U. Xc.
Transient Over Voltage as a Function of Rectifier Stored Charge and Machine Per Unit Comm. Reactance (Xc.)
Device Type :- R720
Bridge Rated at 20 KV, 40 MW.
200
400
600
800
1000
Qrr (μ Coulombs)
Fig 4.

Approximately 3 μF per leg connected in delta across the machine will reduce the transient to within 20% of the normal voltage level under the worst case of Q_{rr} and 0.2 P.U. reactance assuming no further losses to assist us and would represent approximately 5 MVAR of capacitor load.

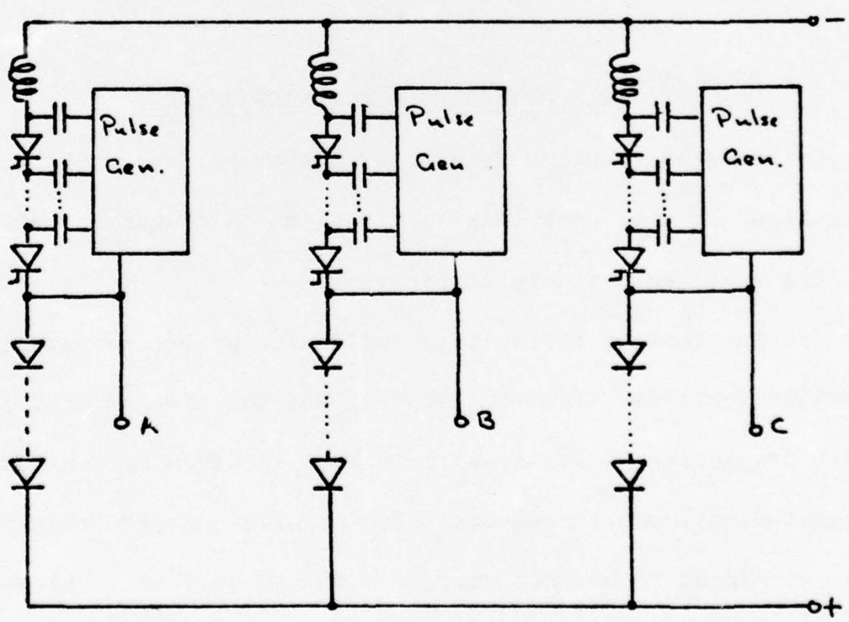
If this solution is inadmissible from weight or size considerations, then standard non-linear surge diverter elements are readily available. The latest zinc oxide (ZnO) devices now under active development in Westinghouse and other labs have remarkably flat voltage/current characteristics above the knee and at the relatively low energy levels we are considering would be hardly stressed at all. Lower voltage ZnO elements are now commercially available and the Trade magazines have been offering higher voltage elements valid at several kV for some time.

12. CONTROLLED RECTIFIER BRIDGES

Comments have been made earlier with regard to using a controlled rectifier bridge. For this application, of course, a half controlled bridge would be a viable alternative.

The problems of overvoltage and device protection are compounded with controlled rectifiers (or thyristors), and the problem of dv/dt, di/dt and reliable triggering of series strings have received much attention. If we exclude the more exotic methods (such as direct laser triggering) there does not appear to be much more that we can do than is already done with the high voltage thyristor modules now in use around the world in HVDC transmission schemes or in the high voltage "flicker" control converters now being installed by Westinghouse.

One alternative to the thyristor bridge might, however, be an RSR (Reverse Switching Rectifier) bridge. This device, made by Westinghouse Youngwood, is now being actively incorporated in Radar Modulators supplied by Westinghouse Baltimore. The present device blocks in both directions, but can be broken over in the forward direction by overvoltage. It has much higher di/dt and peak current ratings than an equivalent thyristor and has been used in series chains up to 35 kV. As there are no individual gate requirements, assembly and wiring is much simpler than a thyristor. It is proposed that a simple high voltage trigger circuit would be adequate to break over each series chain, with the pulse isolated from the machine with some series reactance, as sketched in Figure 5.



Semi-converter Bridge Using R.S.Rs.

Fig. 5

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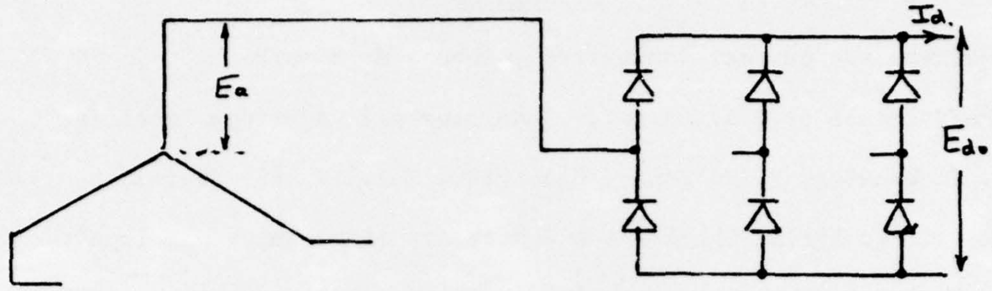
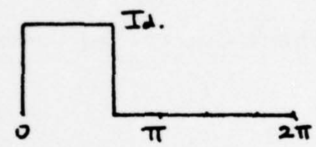
APPENDIX 1

DESIGN FORMULAE FOR THE 3 PHASE BRIDGE WITH WYE CONNECTED SOURCE

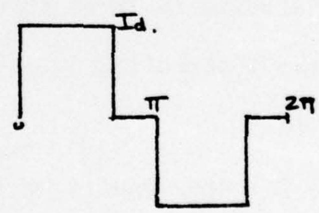




Anode Current

Average Value: $I_d/3$

rms Value: $I_d/\sqrt{3}$



Winding Current

Form Factor: 1.23

rms Value: $\sqrt{\frac{2}{3}}\ I_d$

VA Rating: $\sqrt{6}\ E_a I_d$

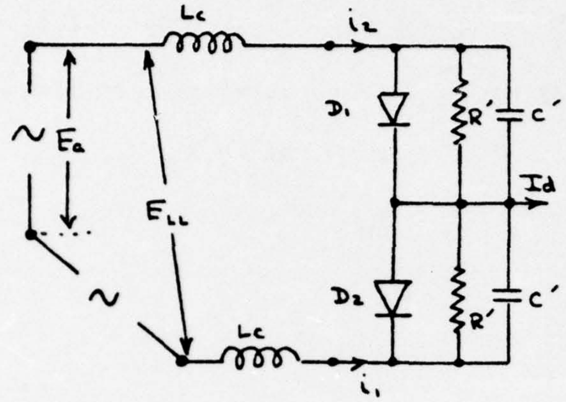
dc Voltage: $E_d = \frac{3\sqrt{6}}{\pi}\ E_a$

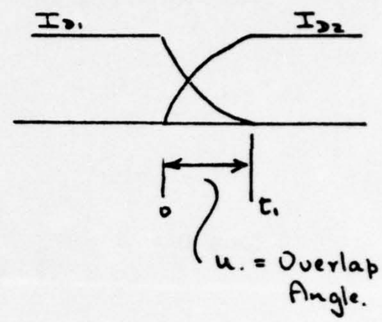
Regulation (Reactive)

$$\text{Voltage Drop} = E_x = \frac{E_{d_o}}{2} \cdot X_{c_{(P.U.)}} \frac{I_d}{I_{d_{max.}}}$$

APPENDIX 2

OVERLAP (OR COMMUTATING) ANGLE FOR A RECTIFIER





L_c = Commutating inductance per line.

R' = Effective resistance across string.

C' = Effective capacitance across string.

Assume polarities shown with D1 going off. At instant of voltage equality, $i_1 = 0$, $i_2 = I_d$. Neglect circuit resistance. The transfer voltage (= E_L) is split equally across reactance of each line.

Total volt time required

$$\int_0^{t_o} E_L dt = 2\int_0^{t_1} L\frac{di}{dt}\, dt \qquad \omega t \quad E_L = E_m \sin \omega t$$

Integrating we have:

$$\left[-\frac{E_m}{\omega}\cos\omega t\right]_0^{t_1} = \left[2 L_1\right]_o^{I_d} \qquad \begin{pmatrix} t = 0,\ i = 0 \\ t = t_1,\ i = I_d \end{pmatrix}$$

$$\frac{E_m}{\omega}\left[1 - \cos u\right] = 2 L I_d \qquad u = \omega t$$

$$\omega L_c = X_c$$

and $E_m = \sqrt{2}\sqrt{3}\ E_a$

$$\cos u = 1 - \frac{\sqrt{2}\ X_c\ I_d}{\sqrt{3}\ E_a} \qquad 2.1$$

Equation 2.1 can be converted into per unit values which is more suitable for our purposes, thus:

X_c = actual ohmic value of commutating reactance/phase.

$= X_{P.U.}\ R$ when $R = \dfrac{E_a}{I_{F.L.}}$ $\quad$ rms phase volts / rms phase current (Full Load)

$$\cos in = 1 - \frac{\sqrt{2}\ X_{P.U.} I_d}{\sqrt{3}\ I_{FL}}$$

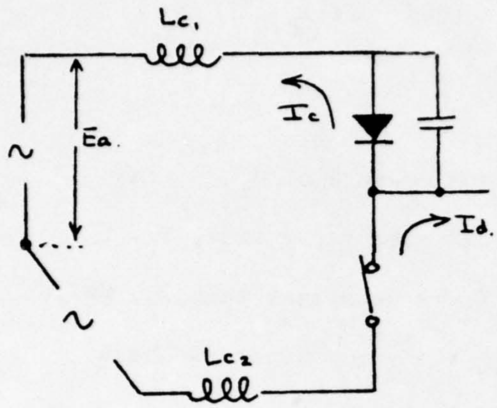
For the bridge rectifier, wye connected, $I_d = \sqrt{\frac{3}{2}}\ I_L$

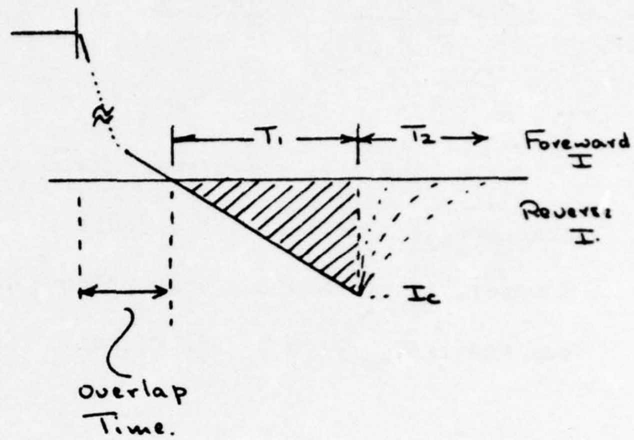
$$\cos u = 1 - \frac{\sqrt{/2}\ \ X_{P.U.}\sqrt{/3}\ I_L}{\sqrt{/3}\ \ \sqrt{/2}\ \ I_{FL}}$$

$$= 1 - X_{P.U.}\ \frac{I_L}{I_{FL}}$$

APPENDIX 3

PEAK REVERSE CURRENT IN A RECTIFIER





Assumptions:

1. di/dt at instant of first current zero (t_o) is maintained constant during T_1.
2. The line voltage (at line frequency) is virtually constant during the T_1 interval.

At the instant, t_o, we have reached the end of the theoretical overlap. At this instant then, the available line-to-line voltage is stretched across the two, phase commutating inductances, i.e., assuming these are equal

$$L_c \frac{di}{dt} = \frac{\nu_c}{2} \quad \text{where} \quad \nu_c = \sqrt{2}\,\sqrt{3}\ E_a$$

But $\quad X_{P.U} = \dfrac{\omega L_c}{R} = \dfrac{\omega L_c}{E_a} \; I_{FL}$ $\qquad$ Subst. we have

$$\frac{X_{P.U.} \; E_a}{\omega . \; I_{FL}} \qquad \frac{I_c}{T_1} \qquad \frac{\sqrt{2} \;\; \sqrt{3}}{2} \; E_a \; \text{Sin} \; (\cos^{-1} \; (1 - X_{P.U.}))$$

The area shown cross-hatched is a measure of Q_{rr}. In practice, the device test circuit shows a finite decay time, T_2. However, if we make one assumption that T_2 is much less than T_1, we can equate Q_{rr} with I_c and T_1, viz. $\quad Q_{rr} = \dfrac{I_c \; T_1}{2}$ $\quad$ Subst. we have

$$\frac{X_{P.U.} \; E_a}{2\pi f \; I_{FL}} \qquad \frac{2 \; Q_{rr}}{T1^2} = \frac{\sqrt{2} \; \sqrt{3}}{2} \; E_d \; \sin \; (\cos^{-1} \; (1 - X_{P.U.}))$$

which on rearranging gives:

$$T_1 = \left(\frac{X_{P.U.} \; Q_{rr} \;\; \sqrt{2}}{\sqrt{3} \;\; \pi \; f \; I_{FL} \; \sin \; (\cos^{-1} \; (1 - X_{P.U.}))} \right)^{1/2} \qquad 3.1$$

The same equation can be arranged, using

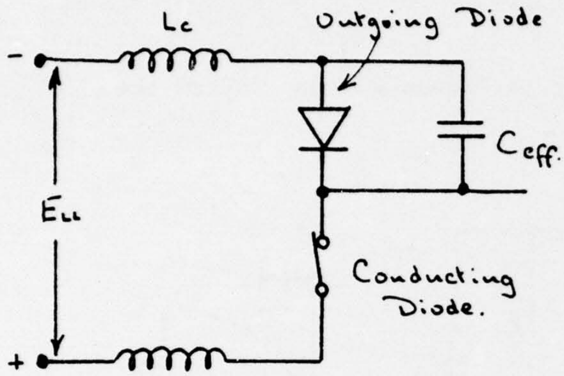
$$Q_{rr} = \frac{I_c \; T_1}{2} \qquad \text{to give}$$

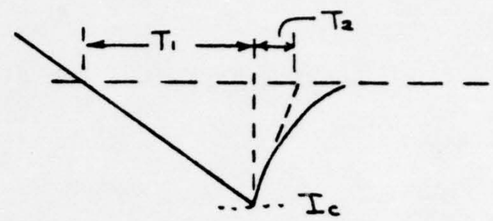
$$I_c = \left[\frac{\sqrt{3} \;\; 4 \; Q_{rr} \; \pi \; f \; I_{FL} \; \sin \; (\cos^{-1} \; (1 - X_{P.U.}))^{1/2}}{X_{P.U.}} \right] \qquad 3.2$$

APPENDIX 4

TRAPPED ENERGY AND OVERVOLTAGE TRANSIENTS

The outgoing diode, at the instant of commutation, is as sketched below:





At the instant of "snap off" (end of T_1) we have $\frac{L_c I_c^2}{2}$ joules of energy stored in the reactance.

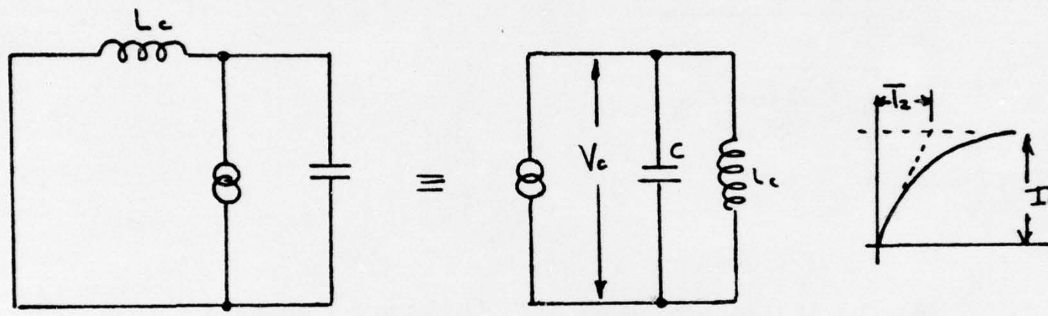
If the diode turns off instantaneously, this energy is passed into the effective shunting capacitance to provide an overvoltage $= \left(\frac{2 \times \text{Joules}}{C}\right)^{1/2}$ volts. This, of course is essentially simplified, since, in practice, C_{eff} will, in any case, charge to equal E_{LL} and would overshoot to $2E_{LL}$ even if the diode turned off at the first current zero.

In practice, I_c turns off at some finite rate which appears to be arbitrary. Estimates for T_2 vary for about T1/2 upwards towards T1/100.

To check whether a finite T2 has much effect (over the usual practical range) we can assume that, for the period of the transient, the supply voltage is essentially constant and by superposition, consider

the transient generation independently of the supply voltage. As far as the circuit is concerned, we are interested in the voltage across the diode (or capacitor) with a current decaying from I_c with a time constant of T2. We can obtain an identical circuit response by removing the diode and forcing a current into the circuit of the same peak value and time constant.

Looking back into the diode terminals we can redraw the circuit thus:



We assume I_o and $V_o = 0$. The impedance transform becomes:

$$Z_{(s)} = \frac{S/C}{S^2 + \omega_1^{\,2}} \qquad \text{where } \omega = \frac{1}{L_c C}$$

The current is given by $I_c\,(1-e^{\frac{-t}{T2}})$ which transforms to:

$$I_c(S) = I_c\left[\frac{1}{S\,(1 + T_2 S)}\right]$$

The voltage across the capacitor

$$V_c(S) = Z(S)\; I_c\;(S)$$

which, on manipulation, gives

$$V_c(S) = \frac{1}{\omega_1^2 C} \left[\frac{1}{(1 + S\,T_2)\,(1 + S^2/\omega_1^2)} \right]$$

which, on transforming, gives

$$V_c = \frac{I_c}{1 + {}_1^2 T_2^2} \left[\frac{T_2}{C} e^{\frac{-t}{T_2}} + \frac{(1 + N_1^2 T_2^2)^{1/2}}{\omega_1 C} \sin(\omega_1 t = \psi) \right]$$

where $\psi = \mathrm{Tan}^{-1}\,\omega_1 T_2$

If $T_2 = 0$ (infinitely fast "snap off"), this equation simplifies down to

$V_C = I_C \sqrt{\frac{L}{C}}$ sin ωt which gives the same answer as equating energies.

Calculations were carried out using a usual peak current of 130 A ($= I_C$), commutating inductance of 1.75 mH and effective capacitance of 0.056 F (typical figures for an 0.2 $X_{P.U}$, 40 MW machine at 40 kV dc) with the following peak results:

$T_2 = 0$	$V_C = 22{,}804$ volts	Reduction $\sim$ 10%
$T_2 = 1\ \mu S$	$V_C = 22{,}692$ "	
$T_2 = 5\ \mu S$	$V_C = 20{,}600$ "	

To obtain an I_C of 130 A, with an L_C of 1.75 mH presupposes a Q_{rr} of 800 µC. This is around the upper limit for the large device and results in a T_1 of 25 µS so that T_2 = 5 µS is relatively fast $(= \frac{T_1}{5})$. It may well be possible that at this operating frequency (400 Hz), we will be unable to afford to use rectifiers which fall into the upper Q_{rr} bands, since this represents approximately six percent of the total period (6 commutations per angle, at 25 µS per commutation).

APPENDIX B

CONVENTIONAL/NON-CONVENTIONAL GENERATOR DESIGN CONSIDERATIONS

APPENDIX B

CONVENTIONAL/NON-CONVENTIONAL GENERATOR DESIGN CONSIDERATIONS

The Westinghouse Aerospace Electrical Division has a wide range of experience in non-conventional machines including solid rotor Lundell generators and inductor generators. Lima Westinghouse has carried out basic development on a 100 KW, 60,000 RPM synchronous permanent magnet generator using rare earth Samarium Cobalt magnets. This generator has features that combine the best of the wound and solid rotor machines and as a result, offers distinct advantages. For instance the rotating field, short flux path of the wound rotor is duplicated by the rotating magnets on the rotor, yet because of the rugged, welded rotor construction containing the magnets, the rotor speed can be very high, typical of a solid rotor machine. In addition, because of the permanent magnets, some surprisingly low reactances are possible, typical of a heavier, wound rotor machine or a twice as heavy solid rotor machine.

In a sentence, solid or wound rotor machines can be compared by stating "for any given (low) shaft speed applicable for a wound rotor, the solid rotor machines will always have second best comparative performance; they can only be competitive when allowed to run at a much higher shaft speed relative to the wound rotor". The two most common solid rotor machines - Inductors and Lundell - can be compared in a sentence by stating: "If the design(er) cannot tolerate a fabricated rotor, one is left with using an Inductor; if fabrication is possible, the design(er) is better off with the Lundell (smoothed rotor) as it can usually show a very slight edge in comparative performance". It should be noted the reason for the development of solid rotor machines for aerospace applications has not been for a weight advantage. Instead, wound rotors for those applications were not compatible with the environment associated with these special applications, e.g., high speed, liquid metal in rotor cavity, high temperature coolant, high pressure in rotor cavity due to gas bearings (required smooth rotors), etc.

A. Inductor

Since flux does not reverse, magnetic steel is used at about 50% efficiency. Therefore, there is about twice the amount of steel required as in

a conventional machine. Excessive steel gives high leakage reactances and armature resistances. Thus, efficiency is penalized and high leakage reactance tends to generate severe spike voltages for rectifier loads. In parts of the magnetic circuit, the flux travels in solid steel. During transients, eddy currents in this steel force the flux to "hang up" which penalizes transient performance by lengthening the time transients. Also, the protruding salient poles of the rotor create very high windage losses unless special steps are taken to obviate them.

The primary advantage of the Inductor is the possibility of brushless high-speed operation in severe environments since there are no windings on the rotor and it can be made from a solid block of steel if desired.

B. Lundell (Also Bekey Robinson, Nadyne or Rice Alternators)

The Lundell has a more or less conventional stator, 3 phase, AC output. However, the rotor poles are cantilevered so that in effect the poles are wrapped around the field coil instead of the coil around the pole as in the conventional salient pole machine. This cantilevering gives rise to severe mechanical problems especially at high speeds, for brushless designs and/or for long stack lengths. Since the rotor flux path is long, weight and transient performance penalties occur similar to those in an Inductor alternator design. Usually part or all of the rotor flux path is in solid steel, which again causes transient response problems.

The primary advantage of Lundell machines is the possibility of operation in severe environments, since there are no rotor windings in a brushless-double air gap machine. Its advantage over the Inductor is that it is usually a smoothed rotor construction having inherently lower windage losses.

C. PM Generator

Permanent magnet generators have the inherent problem of low flux densities available from permanent magnets. Samarium Cobalt is one of the latest state-of-the-art magnets, but even in this case, the useful flux density available is about one-third of densities available in good magnetic steels.

The major advantage is that its performance is much like a conventional machine yet it can take advantage of weight reductions by high speed operation typical of a solid rotor machine. In particular, the present 100 KW PMG model is configured to run at a pole top speed of about 1100 FPS which is at the upper limit of past solid rotor machines.

An inherently severe problem with permanent magnet generators is voltage regulation and ability to turn off completely. The permanent magnets insist on providing flux whether wanted or not. This flux level varies from magnet to magnet, and varies with load. Some regulator schemes have been considered and tried, but they tend to be inefficient.

D. Turboalternator (Wound Rotor)

Another concept that could be considered would be a turboalternator rotor. This concept is not really new for large commercial generators, but it is relatively new for aircraft type generators. A modified turboalternator concept was used for the rotating field of the B-58 generator designed in 1955. The separate slots around each pole supposedly can provide more inherent coil support to each group of coils, thereby allowing higher rotational speeds or tip speeds. In this type construction, the field flux form is obtained by shaping the mmf: in a salient pole machine the flux form is obtained by shaping the permeance of the air gap. As the name turboalternator suggests, the usual advantage of the turboalternator is its adaptability to high speed applications.

E. High Frequency Flux Switched Generator

In conducting a feasibility study one concept to consider would be a "flux switch" generator. This generator has the advantages for this application as follows:

1. Capable of high frequencies.

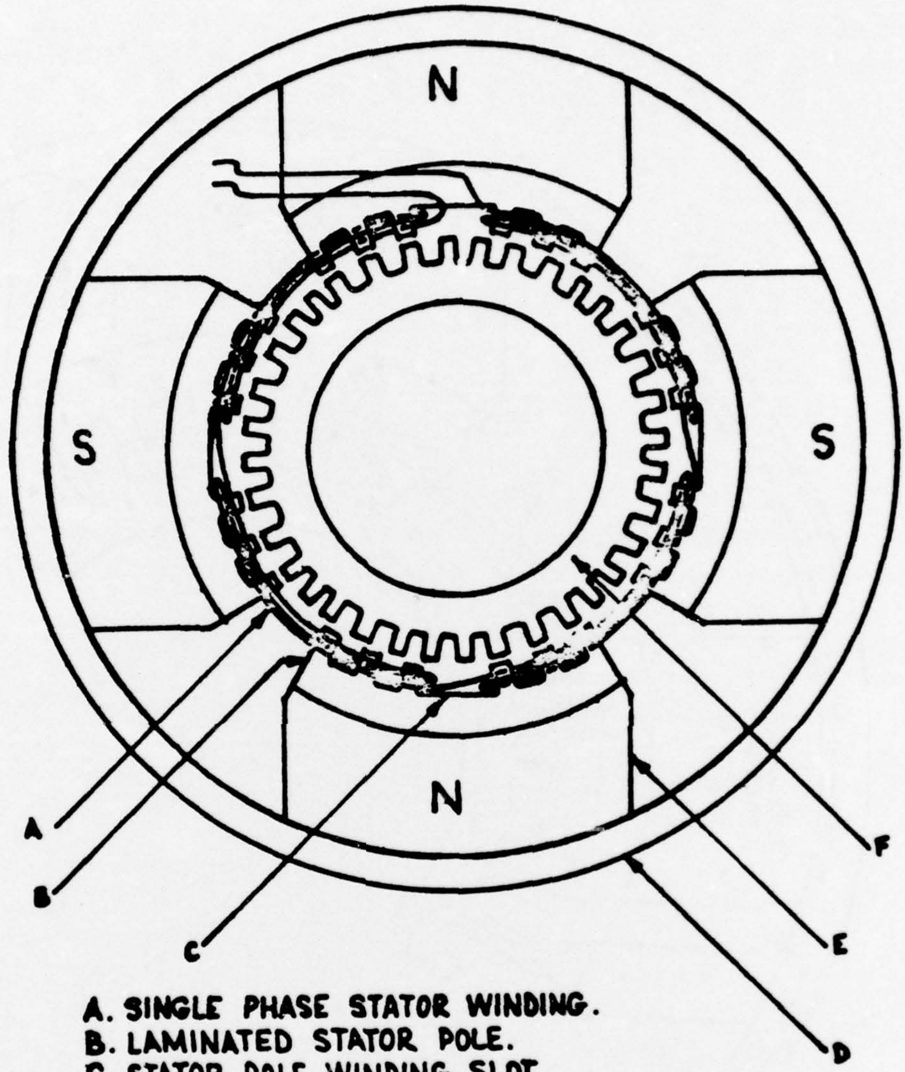
2. Has a "solid rotor" construction with no rotor windings allowing high speed operation.

Westinghouse has manufactured flux switch type generators for many years rated in the order of 1000 watts and 5600 Hz. These are permanent magnet generators used as the source of power to excite the main generators supplying power on commercial and military aircraft.

A description of the flux switch operation is as follows. Refer to Figure B-1. Four permanent magnets are shown as item E and supply North and South flux as shown. The rotor consists of laminated punchings having teeth (item F). Each tooth represents a pair of poles. A laminated stack of punchings (item B) in the poles also have teeth. Half of these teeth on one side of the pole are such that they line up with rotor teeth, when the other half of the stator pole teeth do not line up. When the rotor moves one-half tooth pitch, this interplay between rotor and stator teeth reverses so that those teeth that did not line up - now do; while those that did line up - now do not. Referring to Figure B-2, it is seen that the AC output winding (single phase) encompass half of the pole tip teeth on a South pole and half the pole teeth on the North pole. The action of the rotor and stator teeth is to "switch" flux through the AC winding - first in one direction and then the other direction. High frequency power is thus generated at a frequency equivalent to a conventional generator having twice the number of poles as there are flux-switch rotor teeth.

Although Westinghouse Lima has made small power flux switch machines, it has also made high frequency machines (5600 Hz). Scaling up such a machine to high power applications seems feasible. It would be desirable to use as high a voltage as possible, to keep wire sizes small which in turn would keep eddy current losses in conductors low at the high frequencies. On the other hand, 40 kilovolts is probably too high to expect with present state-of-the-art generator techniques, and a pulse transformer will be required.

At the present time we could visualize a flux switch generator having a rotor 30" diameter by 3 feet long and operating at 12,000 RPM. Compared to small 1 KW permanent magnet machine - a quick estimate says - maybe this would lead to a 10 megawatt generator rated at 5 to 10 kilovolts. Several such machines might be paralleled to supply 40 megawatts of power. Permanent magnets could be useful for field power. However, field power supplied electrically by coils might have the advantage of greater output power capabilities than the 7 to 10 megawatts mentioned.



A. SINGLE PHASE STATOR WINDING.
B. LAMINATED STATOR POLE.
C. STATOR POLE WINDING SLOT.
D. FRAME.
E. PERMANENT MAGNET.
F. LAMINATED ROTOR STACK.

FIGURE B-1. PERMANENT MAGNET, FLUX SWITCH, PILOT EXCITER

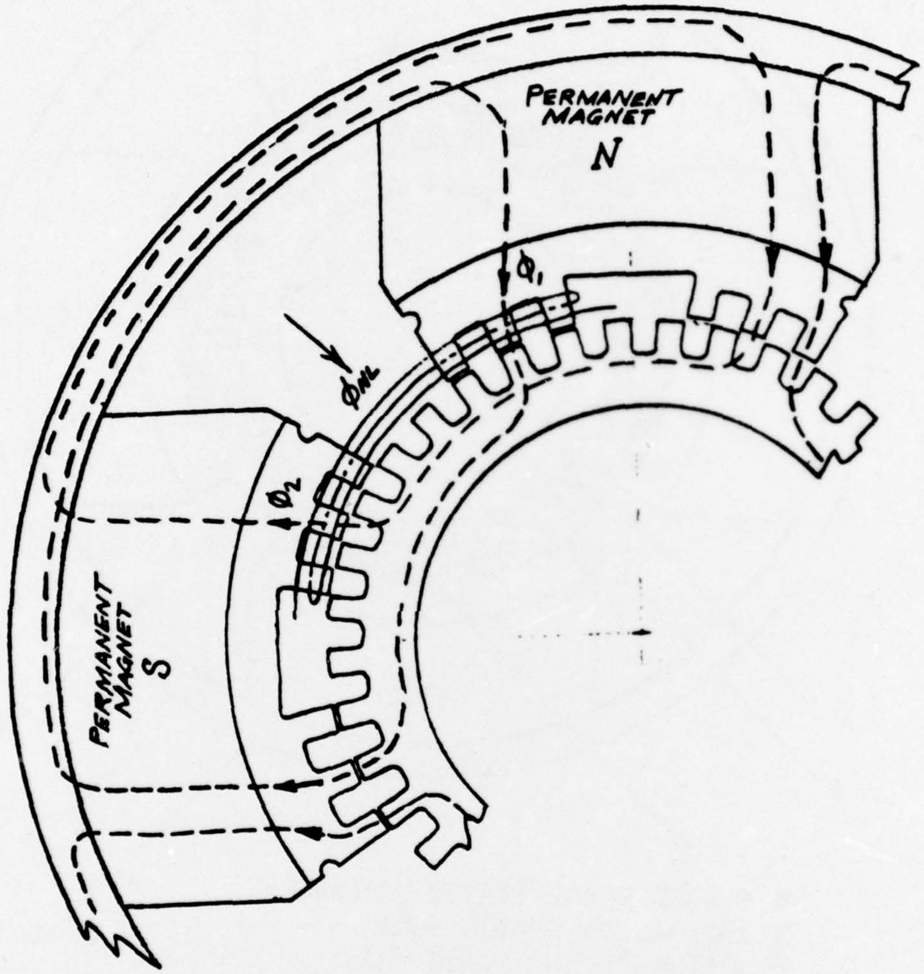


FIGURE B-2. NO LOAD AIR GAP FLUX PATHS

F. Electrostatic Generator

A technique which might be considered is the brushless, rotating plate electrostatic generator. Electrostatic generators employ a variation in capacitance between oppositely charged plates to produce a high voltage, low current output. Variation in capacitance is accomplished by rotating one stack of appropriately spaced plates in the axial spaces between an outer, stationary stack of oppositely charged plates. The output power is proportional to the square of the voltage gradient which may be maintained between the oppositely charged plates. A model electrostatic generator built and tested by Westinghouse Aerospace Electrical Division in shown in Figure B-3.

The brushless, rotating, electrostatic generator has the advantages of relative simplicity of construction, high efficiency (since there are no winding or core losses, and a minimum of windage losses), and high voltage output without the necessity of step up transformers.

However, this machine does not appear to offer much promise as a basis for an electro-mechanical pulse generating machine because of the reasons listed below. These findings were taken from the results of a design and development contract and an independent study performed by the Westinghouse Aerospace Electrical Division in 1963.

1. In an attempt to derive a 300 KW design, it was determined that 50 KW was about the maximum practical size.

2. Excitation requirements are very high, the generator only having about a 3:1 amplification factor. Bulky blocking rectifiers are also required.

3. Specific weights (lbs/KVA) are typically 3 to 5 times those of conventional machines.

4. Must be operated at unity power factor to avoid performance degradation.

5. Medium surrounding the plates must have a high dielectric strength, and to minimize windage losses, should be a vacuum.

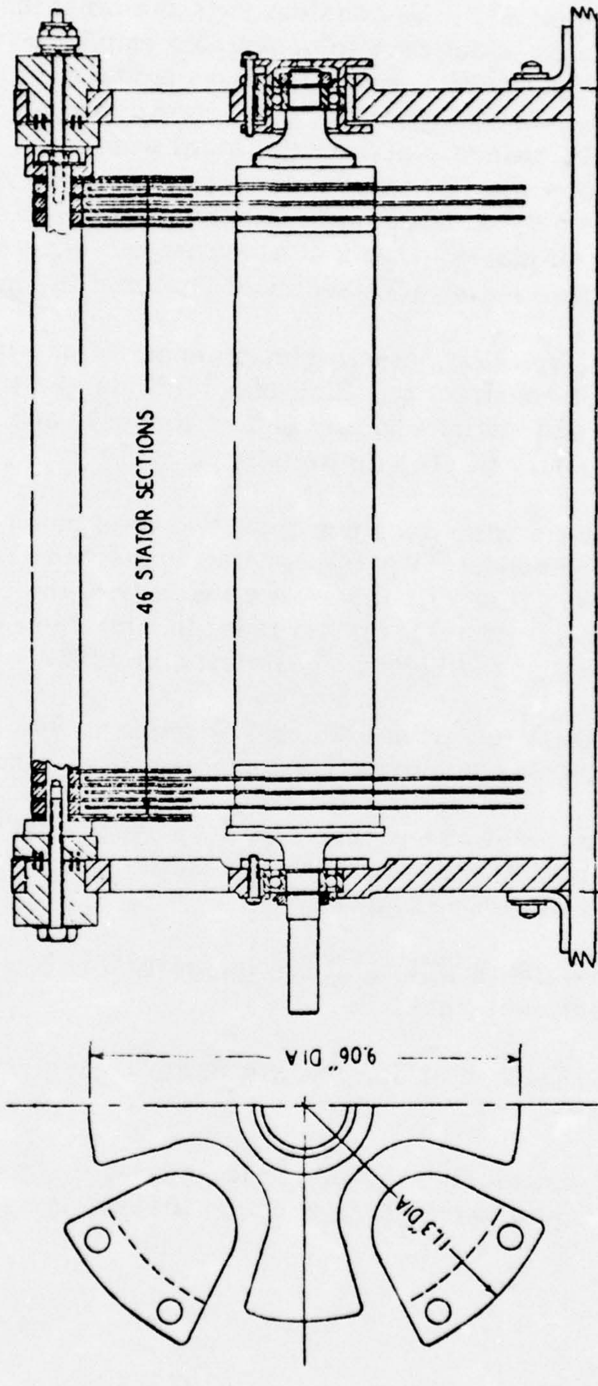


FIGURE B-3 . MODEL ELECTROSTATIC GENERATOR

G. Exotic Methods

The initial survey in this investigation included exotic or unconventional methods of power generation. Most known unconventional sources do not lend themselves to high power pulsed operation. Two of the more promising methods might be:

1. Homopolar Liquid Brush Generator

This approach has been investigated by Rioux, at the Plasma Physics Laboratory of Orsay University (France). It is a unique machine employing no iron, which incorporates a flywheel to store energy. The machine, sketched in Figure B-4, is a unipolar device and is self-excited. It is spun up to speed and then mercury, under pressure, is forced into annular spaces to act as brushes. This self-excites the machine and because there is no iron, the current will build up until resistance limits the current. The machine discussed stores 1.5 MJ in the flywheel and on energizing dumps 0.5 MJ in the load in 0.1 seconds. Unfortunately, from our point of view, the very concept of the machine infers that the output voltage will be low. For example, the machine just quoted, passed 1.1 Megamps but only at 2.2 V at the load. The remaining 4.4V was dropped across internal machine resistances. More recent work has apparently boosted the energy stored up to 10^8 joules, with a discharge pulse of 10^8 A for 0.2 seconds.

2. Flux Compression

A possible unconventional system is the flux compression scheme. Briefly, the technique is a fairly "simple" one in that extremely high magnetic fields of over 10^6 gauss can be obtained by using high explosives to implode a conducting cylinder. The secret lies in making the collapse of the cylinder short compared with the decay of the current in the cylinder. A mechanical hammer type technique could also be used to compress the cylinders.

The first published report appears to have been in 1944 in a classified report by J. L. Fowler, according to C. M. Fowler et al[1] who obtained 10-15 M gauss in a flux compression experiment. From other workers in the field this seemed somewhat high and 4 M gauss seemed to be a more attainable figure.

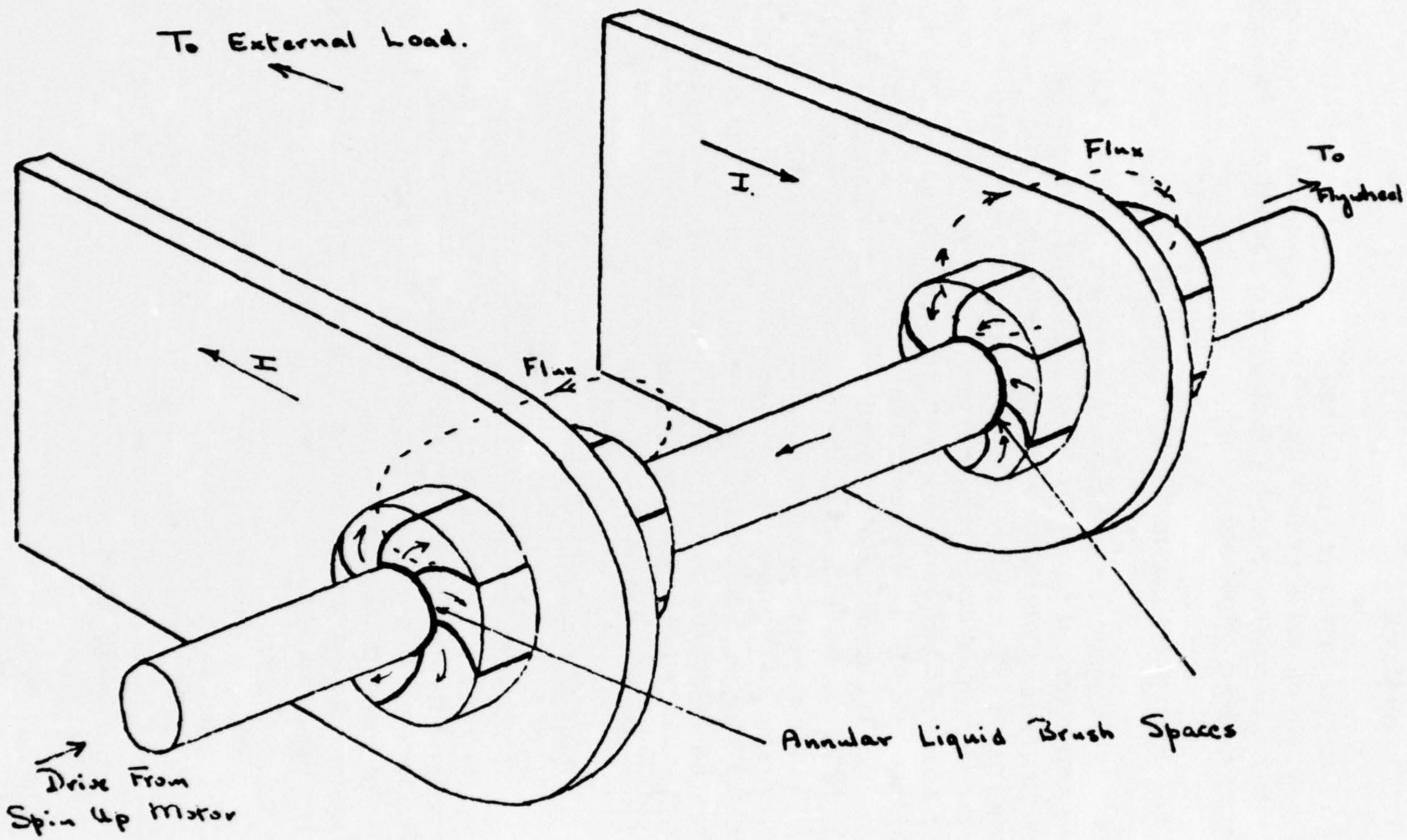


FIGURE B-4. HOMOPOLAR, HIGH CURRENT, LIQUID BRUSH PULSE GENERATOR

Flux compression devices fall into two groups. Those where very high magnetic fields are the end result, called by Knoepfel[2] "Energy Density Generators"; and "Current or Energy Generators" where the end result is a current into a load.

Chemical high explosives release about 4.4 MJ of energy per kilogram. About 10% of this energy can be converted into magnetic field energy and even less (between 1 and 3%) can be transferred to a load. Some immediately available reports [3,4,5] describe some typical experimental "current generators". Test results indicate that currents of several megamperes for pulses of the order of 10-100 μs are readily available. A typical construction might be as sketched in Figure B-5. A fast, high energy pulse is applied to the circuit as shown, building up a high current and hence field (typically 75 kG). At the instant of peak current the explosive is detonated, the short circuiting plate crowbars the initiating current generator and then proceeds up the cone, compressing the flux into the single turn output coil at the end. If this happens to be the load, so well and good. In practice, however, the circuit has basically the same problem as found with magnetic field storage, i.e. having built up the current in the loop, it must then be transferred to the load. This might well be done by making part of the loop a superconductor, allowing it to go normal at some predetermined current and switching the energy into the external load, as sketched in Figure B-5.

The major problem of the flux compression system is, of course, that it is essentially a "single shot" process. The imploded loop must be replaced (together with the explosive) after each shot. This will restrict output unless some form of "machine gun" technique is employed, i.e., explosive charge and collapsible loop are fed in on a belt system. Mechically, there seems no major difficulty in creating such a feed mechanism. One can easily visualize a system which carries forward a pre-formed cone and charge, places it against the output loop, clamps it in position (very similar to a breech block in a gun); makes contact at each end of the cone with the electric pulse generator and ifires the combination. Obviously, at any reasonable pulse rate, the superconductor approach is unfeasible for switching the current to the load because of the delay required to take the conductor back down below critical.

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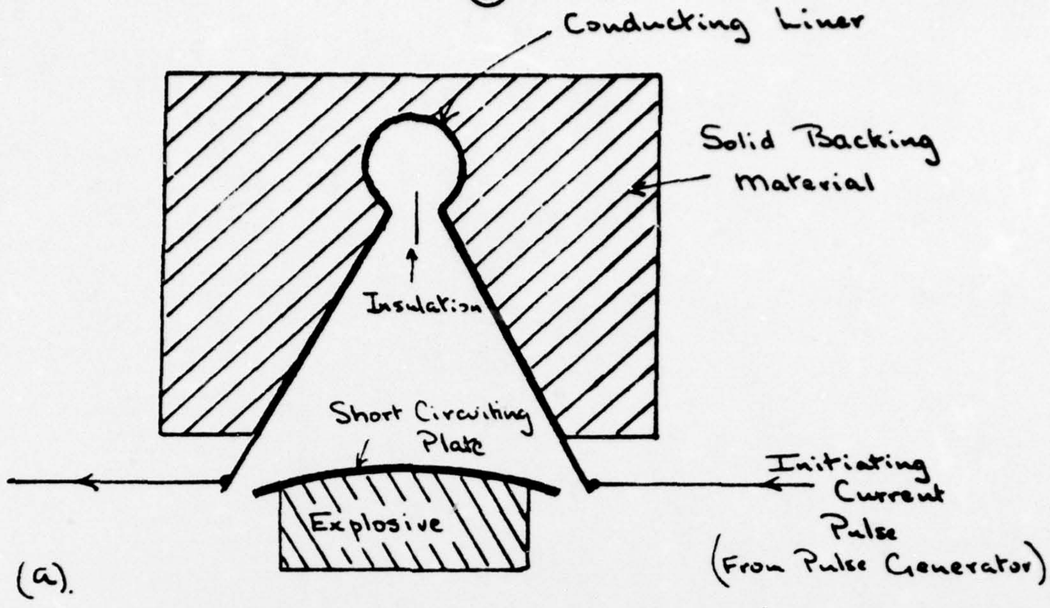
1 "Production of Very High Magnetic Fields by Implosion", C. M. Fowler, et al, J. Appl. Physics Vol. 31, No. 3, March, 1960.

[2]Generation and Switching of Magnetic Energies in the Megajoule Range by Explosive Systems, H. Knoepfel et al, Rev. Sc. Instr., Vol. 40, No. 1, Jan, 1969, pp. 60-67.

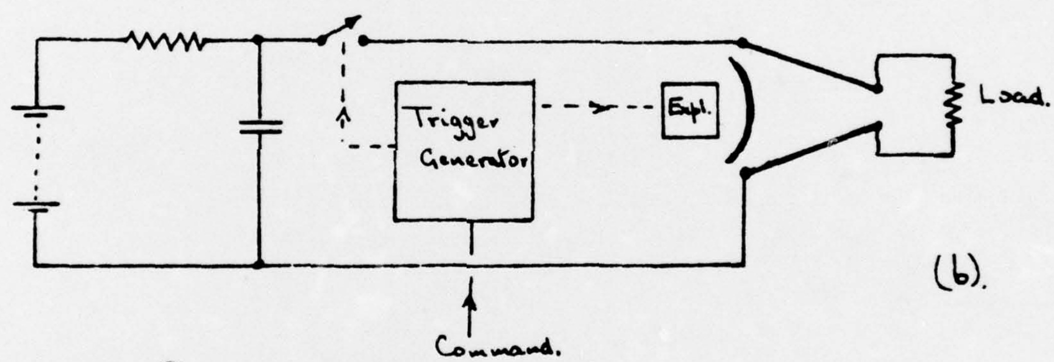
[3]"Megagauss Fields", J. A. Linhart, Physics Today, Feb., 1966.

[4]"Large Electric Power Pulses by Explosive Magnetic Field Compression", R. L. Conger, J. Appl. Phys., Vol. 38, No. 5, April, 1967.

[5]"Production of Large Electric Pulses by Explosive Magnetic Field Compression", R. L. Conger et al, Rev. Sc. Instr., Vol. 38, No. 11, Nov., 1967.



Basic Compression Scheme



Simplified Schematic of (a)

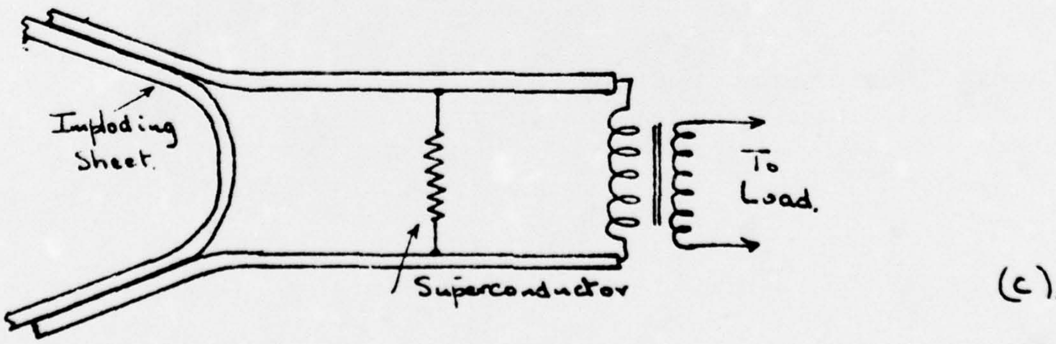


FIGURE B-5. FLUX COMPRESSION

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